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A SURVEY OF RESEARCH METHODS TO STUDY DESIGN

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This report identifies and evaluates methods used by the design research community that could be used to establish requirements for improving the effectiveness of the engineering design process in a Unified Life Cycle Engineering (ULCE) environment. More than 50 design research projects were reviewed to develop an understanding of the scope of design research during the 1970s and 1980s. Reports on these diverse projects are included in an annotated bibliography, which is an appendix to this report. Reviews of the strengths and weaknesses of 18 specific design research projects comprise the body of the report. The methods used in these 18 projects include systems analysis, field observation and participation, retrospective analysis, knowledge representation, protocol analysis, and computational experiments of problem-solving behavior.

14. SUBJECT TERMS

Unified Life Cycle Engineering, ULCE, Engineering Design Decision Process, Systems Analysis, Knowledge Representation, Retrospective Analysis, Protocol Analysis, Meta-Design

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PREFACE

This report was prepared by the Institute for Defense Analyses (IDA) for the Office of Engineering Technology, Deputy Under Secretary of Defense (Research and Advanced Technology) and the Air Force Human Resources Laboratory, Logistics and Human Resources Division, under Contract number MDA 903 84 C 0031, Task Order T-D6-553, "Applications of Systems Engineering Techniques to Development of a Unified Life Cycle Engineering Environment." The issuance of this report meets the specific task of surveying "techniques which have been used in past studies of design processes."

This report was reviewed by Drs. Jeffrey H. Grotte and Frederick R. Riddell of the Strategy, Forces and Resources Division of IDA.

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GLOSSARY

ABET	Accreditation Board of Engineering and Technology
AI	Artificial Intelligence
EDESYN	Engineering Design Synthesis
GE	General Electric
IBM	International Business Machines
ICAM	Integrated Computer-Aided Manufacturing
IDA	Institute for Defense Analyses
IDEF	ICAM Definition Language
IPAD	Integrated Programs for Aerospace Design
MD	Maryland
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NIAM	Nijssen's International Analysis Method
PHIBIS	Procedurally Hierarchical Issue-Based Information System
SA	Structured Analysis
SADT	Softech's Structured Analysis and Design Technique
SUNY	State University of New York
TEAM	Task-Episode Accumulation Model
UCLA	University of California at Los Angeles
ULCE	Unified Life Cycle Engineering

EXECUTIVE SUMMARY

The aim of this study was to gain a deeper understanding of engineering design through the evaluation of the methods used to study the design process. The study focused on determining the methods needed to represent and analyze the design process. This report identifies and evaluates methods used by the design research community that could be used to establish requirements for improving the effectiveness of the engineering design process.

A. BACKGROUND

Unified Life Cycle Engineering (ULCE) is a design engineering environment in which the quality of a product is improved by integrating consideration of producibility and supportability with design attributes for performance, cost, and schedule. The need for ways to model and analyze the design process in an ULCE environment became apparent during the ULCE Architecture and Integration Requirements Study conducted at the Institute for Defense Analyses (IDA) during fiscal year 1987 and funded by the Air Force Human Resources Laboratory [Ref. 1]. This study consisted of examining and developing alternative architectures embodying ULCE concepts. From the beginning of the study, it was clear that the engineering design process is extremely complex, even for relatively simple products. The architecture developed during the study is proposed as a conceptual framework for controlling this complexity. This architecture called for the application of *meta-design*, the design of the design process or, more precisely, the design of the design decisionmaking process.

The meta-design concept developed from the realization that the design process is not generic, except at a very high level. The design process must be flexible, since the design process, and in particular the design decisionmaking process, is driven by the requirements of the product. There will always be more than one way to design a product and more than one sequence of decisions to choose from. The alternate design processes must be evaluated to determine the best method, and to properly evaluate the alternate design processes, some representation of the design process or the design decisionmaking process is required. Research into the methods used to model the design process was seen as the next essential step, and this research was funded by the Air Force Human Resources Laboratory, Logistics and Human Factors Division, during fiscal year 1988. The inherent assumptions of this research are that

- ULCE environments must be based on formal models of the design process.
- A rigorous understanding of design is necessary to develop formal models of the design process.

Additional reasons why studying the design process is of such importance to ULCE have been identified throughout the authors' research activities at IDA. If any portion of the design process is to be automated or if design tools are to be efficiently integrated into the design process, then the design process itself must be fully understood. Additionally, the ULCE objectives will be accomplished only through adequate design education. Design cannot be taught or learned without a thorough understanding of how designers think and function in the design environment. Many of the methods detailed in this report address these issues as well.

B. DESIGN RESEARCH STUDIES

A number of methods, used in past research studies, describe the design process. These methods may be used to study different levels of design activity. Three levels of design activity have been distinguished [Ref. 2] as in Table ES-1.

In this report, design activity at levels 1 and 2 is considered to represent *individual design activity*, and design activity at level 3 is considered to represent *organizational design activity*. Although these two types of activity are distinct, they are interdependent. Both are essential to understanding the design decision process.

When studying design as an individual activity, one is interested in how an individual designer uses innate problem-solving capabilities to solve the design problem, independent of the design environment. These studies attempt to understand the cognitive decision situations faced by a designer and the manner in which personal, empirical knowledge (derived from both formal training and experience) is used to make decisions and solve the design problem.

Table ES-1. Design Activity

Level	Type	Description
1	Decision	Design is described as a value-based process whereby decisions depend on subjective evaluations made by individual designers. Human characteristics of individual designers determine how the design activity proceeds. Decisions made at this level concern minute factors in the design task.
2	Product	Design activity is described in terms of design methodologies. Descriptions at this level attempt to identify and characterize fundamental processes of design activity. These descriptions highlight the multitude of decisions that must be made to create a product.
3	Project	Design activity is described in terms of the communal activity of the team or organization.

Organizational level design studies address the context in which engineering design is done by depicting the decision situations faced by all elements of the design environment. The design organization is composed of a number of diverse functional units (such as design, management, and marketing) and is affected by a number of organizational factors (such as "the nature of the design problem; the constraints of time, resources, work environment, and organization; and the availability and support effectiveness of design aides and tools." [Ref. 3]) Each of these elements influences affects the product life cycle differently. Organizational level design studies attempt to capture the nature of these effects and the interaction among the diverse influences. These studies develop frameworks for understanding how organizations, on a macroscale, make design decisions; how personal knowledge is affected by organizational factors; and how knowledge is shared (communication achieved) throughout the design environment.

More than 50 research projects were reviewed to develop an understanding of the scope of the design research studies throughout the 1970s and 1980s. The design disciplines represented by this collection of studies are diverse and include mechanical, electronics, civil engineering, architectural, interior , and software design. While most of the studies were led by academic researchers, a few were performed by private industry under contract to the Department of Defense.

From this eclectic assortment of research projects, 18 were selected to illustrate the manner in which the design decision process has been studied by the design research community (Figure ES-1). In these studies, attempts have been made to understand design

Researcher/ Institution	Focus	Date Published
Bucciarelli/MIT	Model the design process to explain the role of tradition, habit, and values in technical discourse and decisionmaking	1984
Dyer and Flowers UCLA	Formalize rules of creativity in the area of mechanical design	1984
Eckersley University of MD	Analyze the verbal behavior of designers involved in problem-solving	1988
Findler SUNY Buffalo	Analyze the role of analogical reasoning in design problem-solving by computers	1981
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Green and Brown Worcester Polytech	Analyze the knowledge used and problem-solving behavior exhibited during routine design task	1987
Kalay, Swerdloff, and Harfmann SUNY Buffalo	Develop fundamental paradigms of design as a compatible process	1987
Kurumatani and Yoshikawa/University of Tokyo	Model knowledge of design objects and processes using a formal axiomatic theory of design	1987
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Maher/Carnegie Mellon University	Develop a domain-independent, knowledge-based approach for preliminary design of complex systems	1988
Malhotra, Thomas, Carroll, and Miller IBM TJW Research Center	Identify and characterize important design processes to gain an understanding of aids that can assist the design process	1978
McCall/University of Colorado	Develop a design method for describing design processes and attempting to improve them	1987
Peterson, Hagel, Nadler, and Chignell USC	Identify process and decision aids in design through an analysis of structured interviews	1988
Petroski/Duke	Characterize rational design through the analysis of historical case studies of failures	1987
Promisel, Hartel, Kaplan, Marcus, and Whittenburg/US Army Research Institute	Assess the extent to which human factor issues were considered throughout the development process of four weapon systems	1985
Ullman, Dietterich, and Stauffer Oregon State Univ	Develop a model of the mechanical engineering design process from empirical data	1988
Waldron and Waldron Ohio State	Conduct a retrospective study of the mechanical design process to identify decisions made during conceptual design	1987
Wallace/Cambridge	[illegible] the design process observed in context	1987

Figure ES-1. Design Research Studies Considered in this Report

problem-solving behavior, identify and characterize knowledge used to make design decisions, or represent decision structures of engineering design processes.

The methods used to conduct the research listed in Figure ES-1 can be organized into six categories. Each category represents a unique approach for studying the design decision process. These methods include:

- Systems analysis
- Field observation and participation
- Retrospective analysis
- Knowledge representation
- Protocol analysis
- Computational experiments of problem-solving behavior.

The first three methods listed provide systematic approaches for studying the design process at the organizational level. The last two methods are used to study the design process at the individual level. The knowledge representation method can be used at both the individual and organizational levels; in this report, it is considered at only the organizational level. Figure ES-2 depicts the research projects listed in Figure ES-1 in the context of the classification scheme.

Various methods for studying design at the organizational level are described in Chapter II. Chapter III describes, in detail, some methods used to study design at the individual level. Representative studies employing the method are given, and the advantages and disadvantages of using each method are outlined.

C. OBSERVATIONS

1. Diverse Motivations

A number of diverse motivations drive the study of the design process from both theoretical and practical points of view. For example, groups of investigators throughout the world seek to

- Establish a science of design
- Examine underlying mental processes and cognitive strategies followed during a problem-solving activity

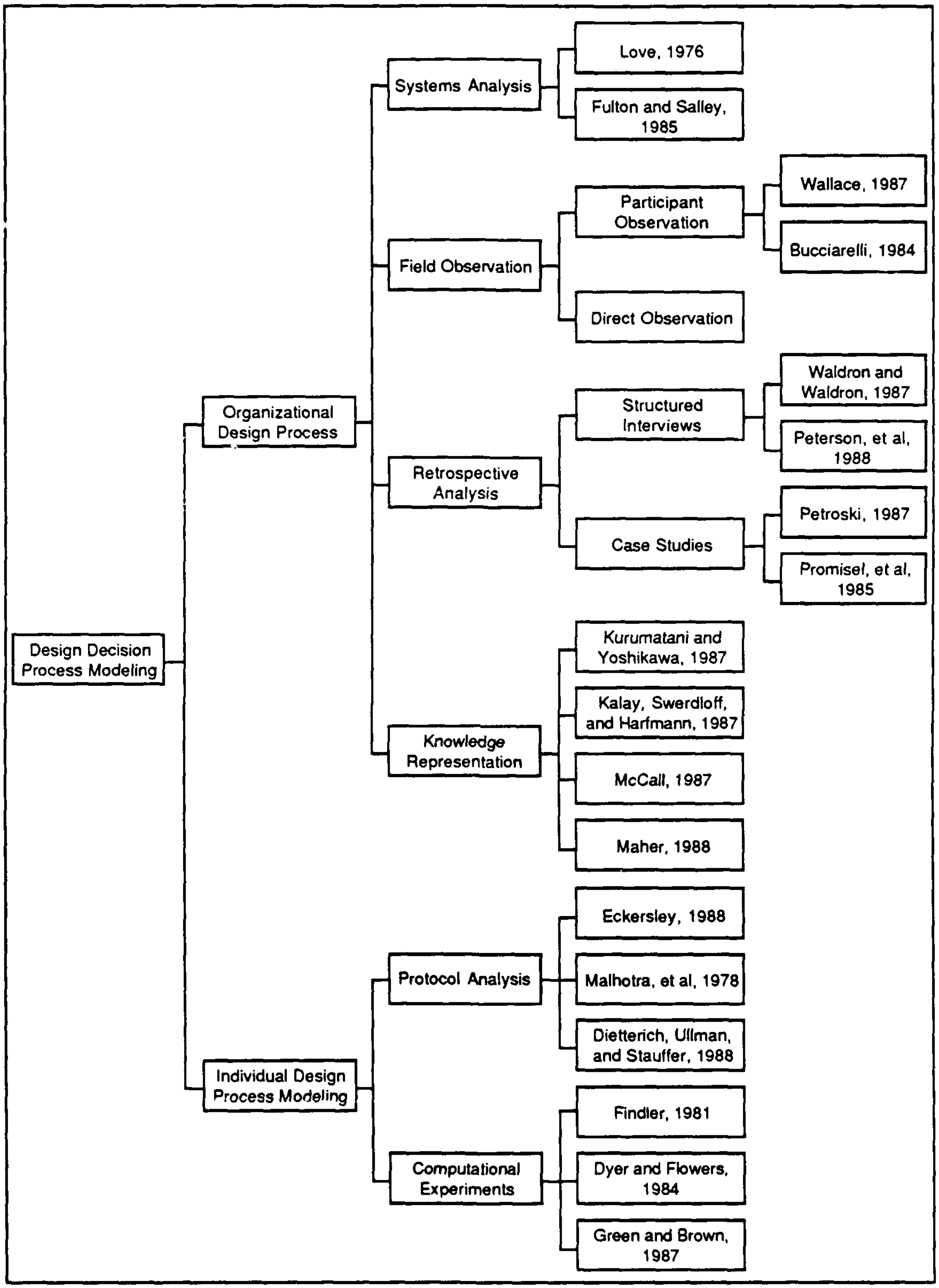

Figure ES-2. Design Research Studies in Classification Scheme

- Understand the industrial and economic implications of engineering design processes
- Develop techniques that could help designers in certain stages of their work, such as brainstorming, synectics,[1] value analysis, morphology, and lateral thinking;
- Develop "systematic procedures to guide the design process" (such as the German VDI-Richtlinien) [Ref. 4]
- Capture design experience by means of expert systems, etc. [Ref. 4]
- Develop improved methods for teaching design.

The abstracts of these surveys are included in the annotated bibliography. Anyone interested in engineering design research should examine these papers in detail before initiating related work.

2. Common Themes

Many common themes underlie the research reported. These commonalities include

- The engineering design problem is an "ill-structured" problem," and thus difficult to solve by any set algorithm." [Ref. 5]
- Design problems are hierarchical and can be decomposed into subproblems.
- Design is both a creative and analytical process.
- Design is a dynamic and iterative process.
- Design problem-solving behavior involves analogical reasoning.
- "The nature of designing requires an interdisciplinary approach." [Ref. 6]
- Design is both a technical and behavioral process; it cannot be studied as though it were one and not the other. [Ref. 7]
- Although a number of attempts have been made to define engineering design, none has been completely successful. [Ref. 8]
- Designers do not attempt to find optimum solutions, rather they attempt to find solutions that work ("satisfice").
- "Many researchers opt for a systems approach." [Ref. 9]

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[1] Synectics is the study of creative processes, especially as applied to the solution of problems by a group of diverse individuals. Synectics comes from the Greek word meaning the joining together of different and apparently irrelevant elements.

- Design decisions are usually not independent.
- There is no interdisciplinary "language of design." [Ref. 6]
- There are few, if any, automated aids for conceptual design. Most design aids are applicable during detail design.

3. Common Definitions

Most of the definitions of the engineering design process suggested by individual researchers closely match those of the Accreditation Board of Engineering and Technology (ABET). Engineering design is described by ABET as

> the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. [Ref. 8]

4. Summary

This report reviews six approaches that have been used by the engineering design research community to examine the design decision process. These approaches yield valuable information about design processes. The approaches, however, result in significantly different types of design decision process information. Table ES-2 is a summary of the types of design decision process information that are typically produced.

The research results are all considered *models* of the design decision process. Although the natures of the models listed in Table ES-2 are quite distinct, each representation serves as a tool for considering the design process problem. Because none of the models considers all aspects of the engineering design decision process, a combination of approaches is required to study design processes in their entirety. As this paper illustrates, the engineering design research community is exploring the application of different types of methodologies to advance its understanding of the design decision process. Motivation for this work is well stated by Simon:

> There are no more promising or important targets for basic scientific research than understanding how human minds, with and without the help of computers, solve problems and make decisions effectively, and improving our problem-solving and decision-making capabilities. [Ref. 10]

Table ES-2. Design Decision Process Information

Approach	Design Decision Process Model
Systems Analysis	Hierarchical, systematic diagrams of the activities, information flows, and influences characterizing a typical engineering design process
Participant Observation	Quantitative (graphs, etc.) and qualitative (narratives, etc.) descriptions of the activities of a particular design project
Retrospective Analysis	High-level frameworks describing the major drivers and decision points of past engineering projects
Knowledge Representation	Formal representations of design decision structures
Protocol Analysis	High-level frameworks that describe the basic components of cognitive activity associated with design problem solving
Computational Experiments	Executable models of problem-solving behavior

I. INTRODUCTION

The aim of this study was to gain a deeper understanding of engineering design through evaluation of the methods used to study the design process. The study focused on determining the methods needed to represent and analyze the design process. This report identifies and evaluates methods used by the design research community that could be used to establish requirements for improving the effectiveness of the engineering design process.

A survey of the design research literature was conducted to determine the methods necessary for representing and analyzing the design process. From this survey, various methods used to model the design process were identified and a classification scheme of the methods was developed. After examining the methods, by considering the results reported in the literature, the strengths and weaknesses of each approach were established.

This chapter provides background information (the motivation for the study) and an introduction to the design research projects. A summary chapter of observations is provided in the concluding chapter.

A. BACKGROUND

Unified Life Cycle Engineering (ULCE) is a design engineering environment in which the quality of a product is improved by integrating consideration of producibility and supportability with design attributes for performance, cost, and schedule. The need for ways to model and analyze the design process in an ULCE environment became apparent during the ULCE Architecture and Integration Requirements Study conducted at the Institute for Defense Analyses (IDA) during fiscal year 1987 and funded by the Air Force Human Resources Laboratory [Ref. 1]. This study consisted of examining and developing alternative architectures embodying ULCE concepts. From the beginning of the study, it was clear that the engineering design process is extremely complex, even for relatively simple products. The architecture developed during the study is proposed as a conceptual framework for controlling this complexity. This architecture called for the application of *meta-design*, the design of the design process or, more precisely, the design of the design decisionmaking process.

The meta-design concept developed from the realization that the design process is not generic, except at a very high level. The design process must be flexible, since the design process, and in particular the design decisionmaking process, is driven by the requirements of the product. There will always be more than one way to design a product and more than one sequence of decisions to choose from. The alternative design processes must be evaluated to determine the best method, and to properly evaluate the alternative design processes, some representation of the design process or design decisionmaking process is required. Research into the methods used to model the design process was seen as the next essential step. The inherent assumptions of this research are that

- ULCE environments must be based on formal models of the design process.
- A rigorous understanding of design is necessary to develop formal models of the design process.

This report and the accompanying report, *Managing Engineering Design Information* [Ref. 11], provide information required to evaluate those models for applicability to ULCE. The research for both reports was funded by the Air Force Human Resources Laboratory, Logistics and Human Factors Division, during fiscal year 1988.

Additional reasons why studying the design process is of such importance to ULCE have been identified throughout the authors' research activities at IDA. If any portion of the design process is to be automated or if design tools are to be efficiently integrated into the design process, then the design process itself must be fully understood. Additionally, the ULCE objectives will be accomplished only through adequate design education. Design cannot be taught or learned without a thorough understanding of how designers think and function in the design environment. Many of the methods detailed in this report address these issues as well.

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From this eclectic assortment of research projects, 18 were selected to illustrate the manner in which the design decision process has been studied by the design research community (Figure I-1). In these studies, attempts have been made to understand design problem-solving behavior, identify and characterize knowledge used to make design decisions, or represent decision structures of engineering design processes.

The methods used to conduct the research listed in Figure I-1 can be organized into six categories. Each category represents a unique approach for studying the design decision process. These methods include

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Wallace/Cambridge	Model the design process observed in context	1987

Figure I-1. Design Research Studies Considered in this Report

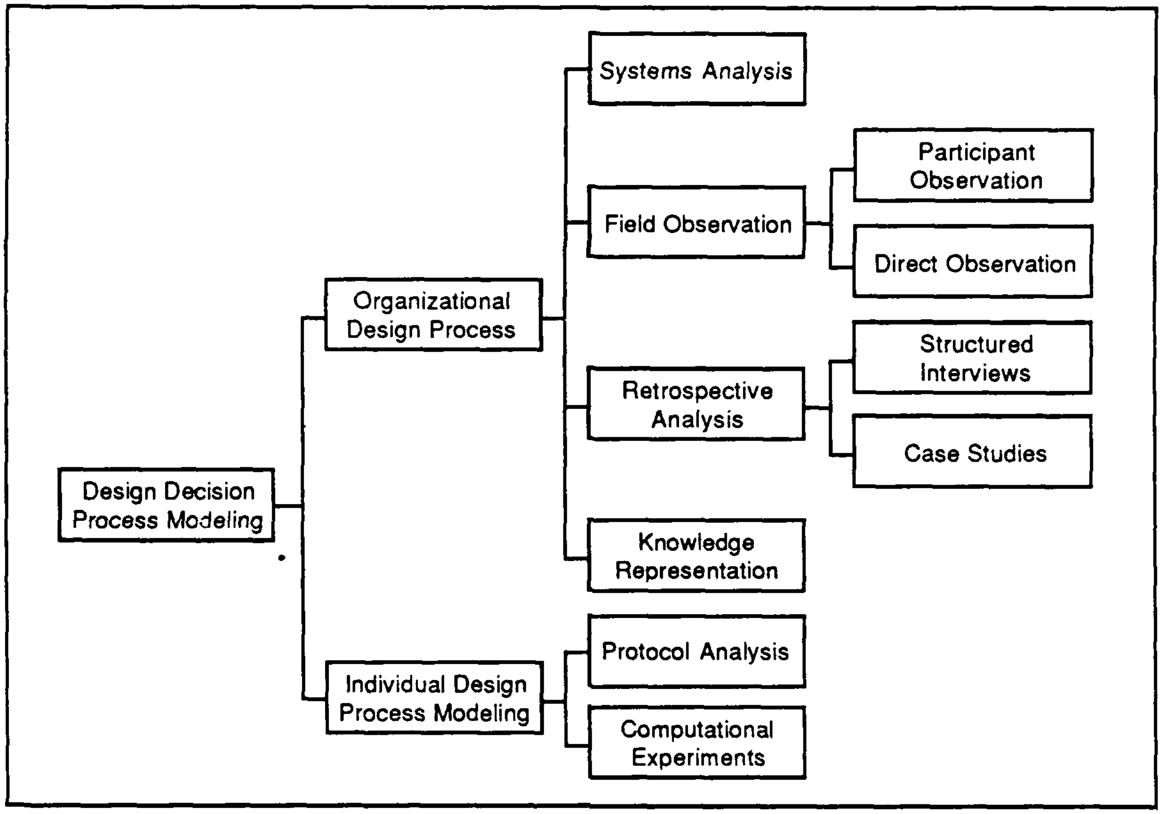

Figure I-2. Classification Scheme for Design Research Studies

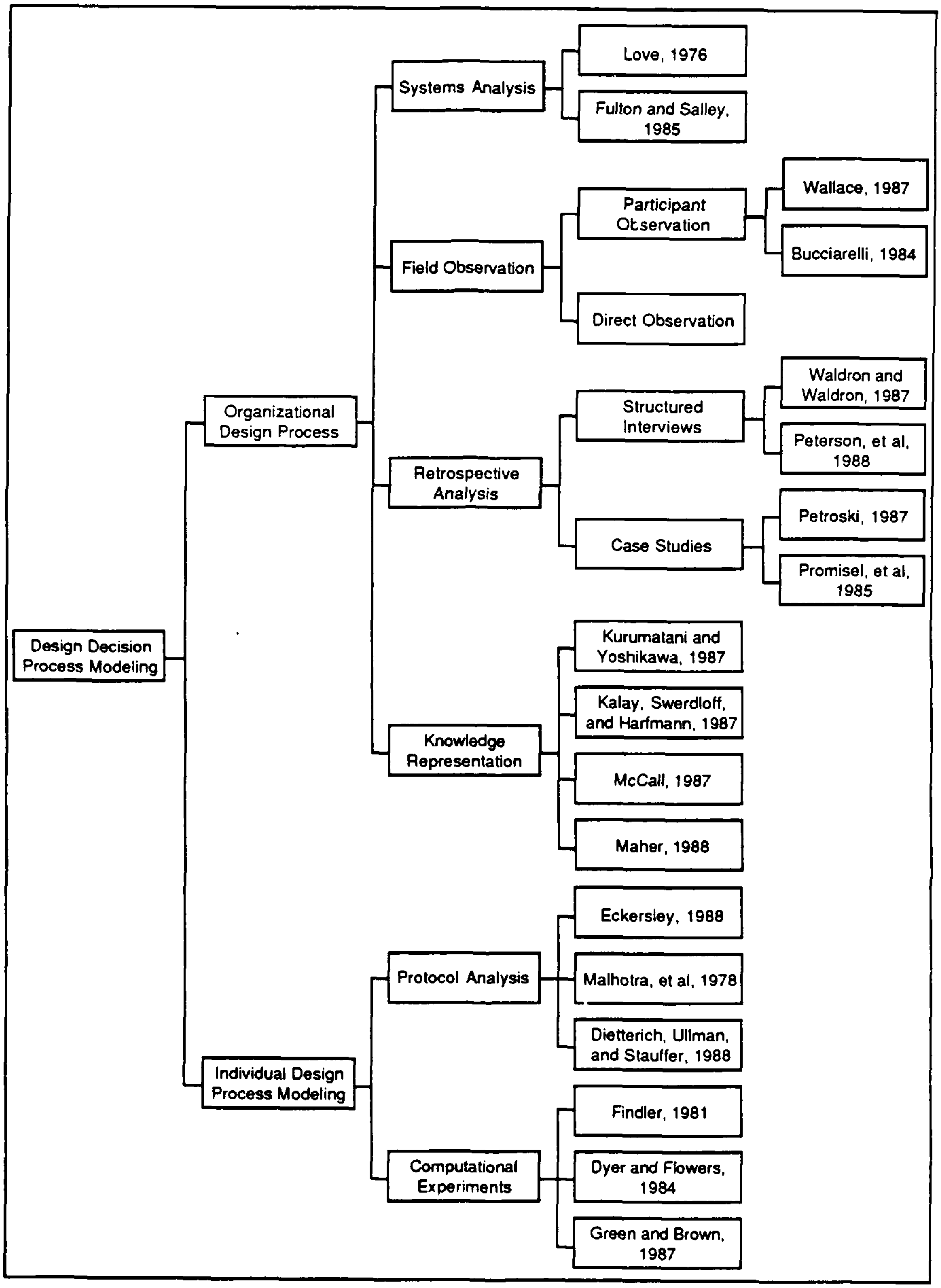

Figure I-3. Design Research Studies in Classification Scheme

II. ORGANIZATIONAL DESIGN RESEARCH STUDIES

This chapter addresses four methods for investigating design decision processes at the level of organizational activity--systems analysis, field observation, retrospective analysis, and knowledge representation.

A. SYSTEMS ANALYSIS

Systems analysis is the application of methodical strategies to identify and describe both significant elements of a complex system (or process) and relationships among those elements. To apply systems analysis techniques, the subject under examination must be amenable to decomposition (i.e., it must comprise discrete elements that are arranged hierarchically and can be independently characterized).

Since the inception of the systems movement, both formal and informal systems analysis strategies have been used to build multi-disciplinary architectures of complex systems and processes. One classical systems analysis architecture views complex systems in terms of *inputs*, *processes* (or functions), and *outputs*. Relationships among functions are established by common inputs and outputs. This is a useful representation for documenting information requirements and flows. Variations to this approach include the identification of *enabling mechanisms*, *technologies*, *constraints*, or *requirements*. Many formal techniques that embody this architecture have evolved over the last decade. These include

- Yourdon's Structured Analysis (SA)
- Gane & Sarson's Structured Systems Analysis
- Softech's Structured Analysis and Design Technique (SADT)
- Integrated Computer-Aided Manufacturing (ICAM) Definition Languages ($IDEF_0$, $IDEF_1$, and $IDEF_2$)
- Nijssen's Information Analysis Method (NIAM)
- Michael Jackson Diagrams

- Warnier-Orr Diagrams
- Hierarchical Input Process Output (HIPO) charts
- Nassi Schneiderman Charts.

These techniques were intended to expedite requirements definition for software development, data base modeling, process design and control, testing, and other systems engineering functions.

Typically, formal systems analysis techniques share the following characteristics:

- The process is viewed from a top-down perspective.
- The system is decomposed recursively (high level elements are defined in terms of constituent subelements, which are in turn defined by subelements, etc.).
- Elements of the system are described in terms of a hierarchical input-process-output architecture.
- The system under study is represented in terms of a graphical notation language with predefined semantics. The graphics describe hierarchies of functions and relationships among those functions.
- Some methodologies include suggested practices for data collection, data assimilation, model reviews, and revisions.

Requirements for the effective application of systems analysis methods to modeling engineering design processes include

- The problem must be sufficiently well defined to render it amenable to decomposition and analysis.
- A well-represented group of interdisciplinary specialists must be actively involved throughout the modeling effort.
- Systematic data assimilation, diagramming, and documentation meth[illegible]es must be established at the inception of the project.
- A clear understanding of how much detail the model will contain must be established at the beginning of the project.
- A clear understanding of the scope of the model must be established.
- A clear understanding of the purpose of the model must be established.

The systems analysis approach to studying design decisions in engineering activity is a top-down examination of the design environment and the elements that influence the environment. Each of the functional components of the engineering design process are identified and studied in detail with respect to the traditional systems analysis architecture (inputs, process, and outputs). The resulting models make it possible to study alternative actions during design.

1. Representative Research Studies

This section describes two very diverse projects that employed systems analysis techniques to understand design decision processes in the software engineering domain [Ref. 12] and in the aerospace domain [Ref. 13].

a. Love

Love [Ref. 12] led a research project at the Space Division of General Electric to study the software development process. The goal of this project was to establish and use a framework for systematically examining and understanding the process of computer program development. The approach adopted was to identify and catalog (with respect to the framework) variables that would significantly influence the development process. The aim of the study was to consider all human and computer activities that contribute to the problem-solving process.

The framework established for this study was patterned after the classical systems analysis input-process-output architecture. Inputs to the process were identified as *task demands*. The key process under examination was identified as the *program development process*. The output from this process was identified as the *operating program.*

The researchers characterized the task demands as both implicit and explicit constraints on the problem. Forms of constraints include descriptions of the problem (these may vary from detailed statements to general and vague descriptions, and they typically change during the course of software development), solution specifications, and resources available (these include the quantity and quality of personnel, hardware, software, and time allocated). The character of these constraints will significantly affect the software development process.

The process itself was characterized in terms of four elements:

- Programmer
- Computer system

- Work environment
- Software development system.

The researchers attempted to describe how each of these elements influenced the effectiveness of the software development process. To assess the potential effect a programmer may have on the process, three classes of factors were identified:

- Intellectual capabilities (cognitive processing capabilities and physiological characteristics)
- Experiences (social, educational, and work)
- Motivations (physical, emotional, and intellectual).

To assess the effect a computer system or systems would have on the efficiency of programmers, three factors were proposed:

- Machine efficiency (speed, capacity, and reliability)
- Mode of operation (hardware and software aspects of the user interface)
- Cost of using the system (overall costs of a system and relative costs of performing certain tasks).

These factors are difficult to characterize as each is complex and potentially multi-dimensional.

The third factor contributing to the effectiveness of the development process, the work environment, was characterized by the following factors and sub-factors:

- Organizational
  - Type and function of the organization
  - Type of work within the organization
  - Organization's reward structure
- Social
  - Programmers' attitudes towards work
  - Programmers' attitudes towards co-workers
- Physical factors
  - Atmosphere
  - Auditory environment
  - Visual environment.

The final factor identified as a major influence on the software development process, the software development system, was characterized in terms of the following four factors:

- Program design (determining a representation for the problem to be solved)
- Program notation (procedures for coding and documenting computer programs)
- Program correctness (proving that an algorithm is correct)
- Program verification (verifying the algorithm's representation in a particular programming language).

This research project provides a framework for examining the environment (and influences) in which design occurs. In defining this framework, the researchers attempted to consider the entire software engineering process, with particular emphasis on "the individual and composite effects of the incredible array of variables which affect the [process]." This genre of framework is appropriate for any engineering activity, regardless of discipline. The value of the framework lies in its use as a tool for structuring raw data gleaned from other studies, such as those considered in the remaining sections of this report (observation/participant, retrospective analysis, protocol analysis, and computational).

b. Fulton and Salley

A series of preliminary studies to support the definition of hardware and software requirements for NASA's Integrated Programs for Aerospace Design (IPAD) program was conducted during the 1970s. The purpose of these studies was to formally document the aerospace design process. Resulting models of the design process were intended to serve as source material for the requirements definition for the IPAD software as described by Fulton and Salley [Ref. 13].

The first round of studies, the pre-contract feasibility studies, were conducted independently by Boeing and General Dynamics. Boeing adopted a functional perspective to examine the product development process for three types of vehicles--a large subsonic transport, a supersonic transport, and a hydrofoil. These examinations resulted in "a detailed picture of the process as a multilayered network of functions." General Dynamics examined the design process from the perspective of individual designers. This resulted in a definition of design tasks, interfaces, and information flow. The net result from both efforts was "a gross characterization of the computer-aided design capabilities needed to support future product developments."

After the official IPAD project was established in 1976 with a contract awarded to Boeing Commercial Airplane Company, a *Design Process Definition Phase* ensued. The authors describe the work during this period as follows:

> The approach taken was to organize a multidisciplinary design team to conduct a systems analysis of the development process for a recent aerospace product, a Boeing 747 commercial air transport. The team prepared detailed logic charts of all stages of design, characterizing design level, the major engineering steps within these levels, interfaces among steps, design iterations, and analysis and design computer programs used to support this work. The 747 study was subsequently expanded to consider other vehicles including a future advanced aircraft (SST), military aircraft (fighter), and a non-aircraft vehicle (hydrofoil).
>
> The system analysis work was also broadened to investigate design interfaces to manufacturing and where major data exchanges take place. This aspect of the study was limited to design/manufacturing interfaces since the ICAM program was well underway to investigate technology associated with detailed manufacturing processes. The studies did, however, include an investigation of how an engineering development was managed through schedule and resource control, tracking, and assessment processes. [Ref. 13]

The models of the aerospace design process were created through the use of a systems analysis technique called the Systematic Activity Modeling Method (SAMM). Using this methodology, the design process was depicted in a network structure, with each node representing related activities connected to other nodes by information flows and feedback. This methodology emphasizes the importance of modeling the data flow among the activities of the design process. SAMM and other classical data modeling methodologies are reviewed and evaluated in the accompanying IDA report, *Managing Engineering Design Information* [Ref. 11].

The IPAD modeling effort is significant because it "provided a system level description of a representative aerospace design process, the first such description available in the literature." [Ref. 13]

2. Strengths and Weaknesses of the Approach

a. Strengths

- The design process is modeled in a systematic and logical manner. The modeling process enables the identification of activities, requirements, constraints, enabling mechanisms, data flows, decisions, informational interfaces, and relationships.
- This approach models complex design environments "in such a way that one can study part of the [environment] at a time while not losing the overall context." [Ref. 14]
- "Formal models are useful for doing further analysis to see if the description of a [design environment] is correct and consistent." [Ref. 14]
- The resultant functional diagrams serve as a tool for interdisciplinary communication, meeting control, design reviews, etc.
- Models produced as a result of systems analyses are tools for addressing the following questions:
  - What are the interrelationships among constituent subprocesses? (How does the behavior of one subprocess affect others?)
  - What functions (or subprocesses) have common elements (such as common components) or common data flow?
  - How do the various team members affect the processes identified?
  - Are there any redundant or conflicting subprocesses?
  - Is the information flow reasonable?
  - Is there unnecessary information provided to certain subprocesses?
  - Is there any missing information required by certain subprocesses?
  - Is the process needlessly complicated?
  - Can any aspects of the process be streamlined?
  - Are there any major problems in the design process?
  - What are the boundaries of particular subprocesses?
- The modeling process is highly iterative and becomes a valuable experience for enhancing communication and cooperation among team players.

b. Weaknesses

- This approach focuses on static aspects of design processes and is sequential in nature; it does not capture behavior patterns that emerge over time or temporal information inherent in concurrent processes.
- The resulting functional diagrams are typically very large, detailed, and difficult to read. The terms used on the diagrams are usually defined ambiguously or vaguely, if at all, so understanding the diagrams requires complete understanding of the terms and graphics used. Typically, only those actively involved in the development of the model can read or make use of it.
- The resulting models usually do not include the assumptions they are based on.
- The human-machine interface area is usually neglected. [Ref. 15]
- The resulting models cannot be verified for completeness or consistency.

B. PARTICIPANT OBSERVATION STUDIES OF DESIGN ACTIVITY

Participant observation studies (also referred to as *informal reporting* or *direct observation*), a well-established research methodology in the social sciences, are gaining acceptance within the engineering design research community. Although an informal methodology, researchers are beginning to regard this approach as a viable means of gathering data to answer questions that are highly context-dependent. The participant observation methodology offers a flexible and dynamic approach for examining the multidisciplinary and multifaceted nature of the design process. Meister explains the need for this type of approach:

> It is impossible to understand design, and in particular how behavioral inputs are handled in design, without examining its sociocultural context. The role the engineer plays vis-a-vis his superiors (the management) and other contributors to the design process has significant implications for design efficiency. [Ref. 16]

The participant observation method basically consists of three dimensions:

- The design activity is carefully observed within the industrial design organization.
- The researcher participates in the activity.
- All observations are recorded and all temporary and final artifacts of the process are preserved.

Useful descriptions of participant observation studies are provided by design researchers who have employed this approach. Wallace simply describes participant observation studies as those in which "the researcher actually participates in the design process, both contributes to it and observes it at the same time" [Ref. 17]. Bucciarelli describes this approach as a "naturalistic, observational method of study, yielding descriptions of complex phenomena" [Ref. 18]. He explains:

> In order to better understand the engineering design process, I go into the firm much as an ethnographer might enter a remote village to study an aboriginal culture. I not only observe but also participate as an engineer in the day-to-day work of design and in this way my study differs from that of the anthropologist far from home. I join the world of participants in design, a world that at first strikes me as chaotic, but then with time, settles into a more comfortable but still complex process.

The raw data collected in this manner is used to compile analytical descriptions of the design activity. These descriptions are not only broad in scope but also typically very detailed. Furthermore, because the data is organization- and product-specific, the resulting descriptions are also.

The successful application of participant observation research techniques requires, at a minimum, the following three conditions to be met:

- The practice of a systematic design methodology by the design team (i.e., Pahl and Beitz). This provides coherent structures for categorizing data and comparing theory and practice. [Ref. 17]
- Participation by the researcher from the inception of the design project to the fielding of the product.
- "Large measure of support and cooperation from the design team." [Ref. 17]

With respect to studying design decision processes at an organizational level of activity, Simon makes a number of interesting remarks :

> Decision making in organizational settings, which is much less well understood than individual decision making and problem solving, can be studied with great profit using already established methods of inquiry, especially through intensive long-range studies within individual organizations....
>
> Although the decision-making processes of organizations have been studied in the field on a limited scale, a great many more such intensive studies will be needed before the full range of techniques used by organizations to make their decisions is understood, and before the strengths and weaknesses of these techniques are grasped.... [Ref. 10]

The projects described in the following section represent two such intensive and valuable studies into engineering design decision processes using the participant observation approach.

1. Representative Research Studies

a. Wallace

Wallace [Ref. 17] is involved in a design research program at the University of Cambridge which focuses on how the performance of design teams can be improved. As part of this research program, a "detailed participant observation study of an engineering design project in industry" was initiated in 1982. The goal of this study was to "carry out an exploratory investigation into the research methods and likely outcomes of studying a team working through the engineering design process in industry."

The approach adopted for this study consisted of participant observation methods to collect and analyze data generated throughout the design process. Raw data collected during the study included field notes, correspondence, design notes and drawings, weekly reports, technical reports, audio tape recordings, and case histories from other projects.

Prior to massaging this raw data, the researchers found that a model was needed to organize the data that was being collected. As the author explains:

> During the Cambridge project, many of the available models of the design process were reviewed, but none was entirely satisfactory for structuring and analyzing the data. Using the existing models as a starting point, a new diagrammatic model was developed which set the design process in a broad industrial context and identified five hierarchical levels of resolution. This provided a satisfactory framework for analyzing the data from the particular design project studied, but whether it is valid for other types of projects is impossible to say at this stage. [Ref. 17, Figure II-1]

This model is unique because it distinguishes between the overall project effort and the engineering design process. It was designed to be used to classify inputs to the projects at different levels within the context in which engineering design occurs.

Essential elements from the raw data were compiled into *interchange data sheets*, which were subsequently transferred to a microcomputer data base and analyzed by means of spreadsheet calculations. From this data base, the researchers were able to generate analytic reports and graphs that described elements such as the following:

- Each participant's work effort
- Amount of time spent on the different phases of design
- Amount of time spent in meetings
- Use of methods and aids
- Distribution of work effort completed in various locations
- Quantified measures of subjective data on the mood of participants.

These quantitative analyses described the design project in terms of the activities and outputs produced but did not explain the reasons behind the process. To address this issue, the researchers attempted to identify influences that affected the project. The influences were characterized with respect to the five levels of resolution defined in the context model and were characterized in terms of observed contributing factors. With this framework, the researchers were able to examine which influences [Figure II-1] had the greatest observed effect on the design process. These examinations led to an attempt to profile the project according to the effect of the influences.

With this myriad of derived information, the researchers were able to characterize the project in terms of quantitative and qualitative measures. The analytical reports, analytical graphs, narrative case histories, and influence charts provided the means to attain a deeper understanding of the activities, outputs, and influences of the engineering design process.

b. Bucciarelli

Bucciarelli [Ref. 18] is conducting research at the MIT School of Engineering to develop a better understanding of the engineering design process. He is specifically interested in exploring "the social as well as technical elements of decisions made in a firm's endeavor to develop and market its wares." To do this, a long-range participant observation study was initiated in 1982. The principle objective of this study was to "determine how values inform decisions and thus affect the forms of technology that emerge from that process."

Level of Resolution	Influence Category	Examples of Contributing Factors
Macroeconomic (Environment)	External	Social/Political/Economic/Ecological/Legal/Random
Microeconomic (Market)	Market Resource Availability Customer	Demand/Competition/Risk/Finance/Services/People Need/Urgency/Expectations
Corporate (Company)	Corporate Structure Corporate Systems Corporate Strategy Shared Values Management Style Management Skills Management Staff	Size/Span/Complexity/Integration/Remuneration Objectives/Risk-Taking/Commitment/Enthusiasm Autocratic/Benevolent/Coordinating/Resource Use Judgment/Confidence
Project	Design Task Design Team Design Techniques Design Output	Magnitude/Complexity/Risk/Novelty/Quantity/Timing Expertise/Experience/User/Role Balance/Motivation Systematic Procedures/Communicating/Motivating Productivity/Quality
Personal	Personal Knowledge Personal Skills Personal Attitude Personal Movitation Personal Output	Knowledge Base/Usefulness/Perception Imagination/Self-Discipline/Integrity/Enthusiasm Involvement/Productivity/Quality

Figure II-1. Design Process Influences

Throughout the course of this study a vast amount of raw data is being collected, including:

- Field notes (conversations; sketches; informal meeting proceedings; language used; gestures; sources of problems, interruptions, and delays; and other observations of daily activity)
- Design review notes
- Formal engineering drawings
- Managerial charts
- Product specification sheets
- Employee newsletters
- Formal interviews with designers
- Audio tape recordings of designers' ideas and impressions.

Bucciarelli is in the process of developing a comprehensive framework for analyzing the raw data. The results of this analysis will be a model of the design process in terms of the "the role of tradition, habit, and values in technical discourse and decision making." He is working with two different forms of representations--narrative case studies and topical classification schemes to structure the data. With these models, he intends to reveal "the character and consequences of the discourse through which design participants communicate with each other under conditions of sustained uncertainty and ambiguity." These descriptions of the design process will explain such observations as:

> ...different participants in the design process have different perceptions of the design...The task of design is then as much a matter of getting different people to share a common perspective, to agree on the most significant issues, and to shape consensus on what must be done next, as it is a matter of concept formation, evaluation of alternatives, costing and sizing.... [Ref. 18]

2. Strengths and Weaknesses of the Approach

a. Strengths

- The participant observation approach "provides the [resercher] opportunity to *experience* the design activity and increases the chances of being aware of the many subtle factors and influences which affect the cou`e of the project. It also provides a limited opportunity to try out some ideas and methods. For instance, a particular design approach can be used to coordinate the design team and influence its progress." [Ref. 17]
- This approach is useful for eliciting information that is difficult to express.
- This approach highlights the complexity of the human interactions involved in the design process. [Ref. 18]
- "Participant observation offers the potential for gathering a very large amount of quantitative and qualitative data, and it provides the opportunity for testing out a limited number of ideas and methods." [Ref. 17]
- The data that is collected serves as sources of input to other forms of empirical inquiry such as computational experiments. [Ref. 19]

b. Weaknesses

Wallace provides a number of observations from the study he conducted regarding weaknesses in this method. These include:

- ...with participant observation the problems for the researcher increase, and include:
  - (1) Gaining the complete confidence of the design team;
  - (2) Splitting the time between 'participating' and 'observing';
  - (3) Maintaining a neutral viewpoint and keeping the observations impartial while being closely involved in the project.
- It falls short of a planned experiment. [Necessary to systematically study a particular theory]
- The procedure...is very laborious.
- Every hour spent recording data required at least another hour to write up and reference the data.
- Difficulties arose during data collection, processing, and analysis. [Ref. 17]

Additional weaknesses identified include

- Recording anything other than what is written down or retained in other tangible forms is difficult. [Ref. 20]
- One cannot replay the design episode to do a detailed analysis of what occurred; only a momentary analysis, while one is observing and participating, is possible.

C. RETROSPECTIVE ANALYSIS

The examination of retrospective reports, case studies, and other forms of historical research is a traditional and universally employed approach for deriving general principles to describe complex phenomena. Accounts of past events from a suitable variety of perspectives and domains provide rich sources of raw data for drawing generalizations about the nature of design. With this data, design researchers are able to identify fundamental factors associated with both successful and disastrous design.

The type of information that can be gleaned from a retrospective report depends on the purpose of the report and the manner in which the report was generated. A typical case study, prepared for historical purposes, describes the design project in terms of discrete phases. For each phase, the following types of raw data may be provided:

- Task descriptions
- Requirements and constraints

- Predetermined decision points
- Manner in which the tasks were accomplished
- Expertise and knowledge required
- Technical parameters selected
- Parameter dependencies
- Sizing of the parameters
- Manufacturing considerations
- Artifacts of the design process
- Analysis tools used
- Type of reviews conducted
- Type of tests conducted
- Subject of tests
- Design and manufacturing interface
- Quality assurance requirements
- System integration requirements
- System integration tests
- Role of the designers in the field support.

With this raw data, the following types of information may be produced:

- Patterns in design processes that led to solutions
- Commonalities in design processes across all domains
- Problem areas
- Important design decisions
- Effect or influence of decision makers
- Reasons for the decisions
- Information used to make design decisions
- Evolution of the project knowledge base
- Effect of internal procedures
- Effect of organizational constraints
- Effect of the types of tasks and activities conducted in the past

- Manner in which the product evolved
- Characterizations of the organizations
- Characterizations of the people involved
- Effect of external influences
- Relationships among the engineering function, management, and indirect personnel
- Relationships among internal and external influences
- Effect of tools and techniques employed.

With this information, analyses of case studies serve as a basis for defining, testing, and refining generic models of the design process.

Retrospective reports are often narratives provided by key individuals involved in the design project. These reports cover significant, specific aspects of the project. Other sources of historical data include responses to structured and unstructured interviews or questionnaires, project documentation (technical, administrative, and managerial), and any other informal account of the project history (such as press releases). Of these modes of data collection, interviews provide the most flexibility and promise of attaining the information required. As explained by Magee [Ref. 2]:

> Interviewers can make sure respondents have understood any question and the purpose of that question. They can probe further when a response warrants it; ask the expert to clarify a response so that it is understood; and pick up clues from the expert's non-verbal communication about the dependability or otherwise of the information. Perhaps more importantly interviewers can build up a rapport with experts and create an atmosphere in which they find it easier to communicate...

To analyze source data, a framework that structures the data in terms of specific aspects of the design process is required. Such a framework serves as the primary tool for answering research questions about design processes. The framework created by Waldron and Waldron [Ref. 7], described in the next section, is an excellent example of the manner in which retrospective data can be structured to identify the major design decisions that were made during the design of a complex mechanical system.

Examining the design process a posteriori yields valuable insights into the design process. The following conditions, when met, increase the effectiveness of retrospective analysis:

- The design project must be well documented, including frequent reports from a variety of perspectives covering a number of aspects of the design process.
- The entire project team must be available to answer questions about the project, including key individuals and others who directly or indirectly affected the design.
- Primary and secondary issues must be identifiable from the source material.
- All historical information must be placed in a time sequence.

1. Representative Research Studies

In this section, the ways in which various researchers have examined case studies of design projects to understand the design decision process is presented.

a. Waldron and Waldron

Waldron and Waldron [Ref. 21] are conducting research at Ohio State University into the conceptual mechanical design process. One aspect of their research consisted of a retrospective analysis of the system design of the Adaptive Suspension Vehicle developed in the Department of Mechanical Engineering, Ohio State University. The results from this study are intended to contribute to the foundation of a theory of the mechanical design process.

The research methodology used in this study involved collecting case history information and formulating a model of the design decision process from the retrospective reports. The case histories were narratives (from the principle engineer of the project) describing the evolution and final outcome of the design concepts produced throughout the project. The principle engineer (and others involved in the design) were asked to "recount the state of the knowledge at each decision point [in the design process] including misleading and erroneous knowledge."

With the retrospective narratives, the researchers developed a model of the design decision process for this particular product. The representation is in the form of a chart that shows the following:

- Major events in the design process (design decisions, subsystem phases, and other events affecting the design process)
- Major events in the manufacturing process
- States of the knowledge base over time

- Information pathways
- Events peripheral to the design and manufacturing processes that helped establish an environmental timeframe.

This model is organized chronologically so that the evolution of the knowledge bases used to make design decisions and the progression of the development of design concepts can be examined and tracked.

Using this model, much analysis was possible. It was used to identify issues involved in major design decisions and examine the way decisions were made. From this analysis, the authors were able to draw general conclusions about the design process of this particular product which led to a theory of the mechanical design process. The authors suggest that this is "a reasonable approach for identifying an organizational structure of the design process...[using]...major design decisions as the organizing principle" [Ref. 21]. More important, the model provides a solid foundation for the analysis of data generated as the result of other methodologies at the individual level, such as protocol analysis [Section III-A].

b. Peterson, Hagel, Nadler, and Chignell

Peterson, Hagel, Nadler, and Chignell [Ref. 22] are conducting research at the University of Southern California to "identify and investigate process and decision aids in design." The methodology developed for this project, loosely based on Nadler's Timeline Scenario Methodology, is called *Retrospective Timeline Scenario Methodology*. This method consists of conducting carefully planned structured interviews in which the interview questions are designed to elicit comprehensive information describing the activities and processes that occurred during a successful design project. The case study data are gathered from a timeline perspective and are organized in a temporal manner. The model generated is a timeline scenario that "shows relationships between various elements (such as people, information, activities, modes of communication, and critical events) over time (time is the X-axis)."

While results from the initial phase of the study are under formation, some preliminary findings include:

- In some cases, the interviews yielded more questions than answers.
- A number of elements of design processes were identified.

- Established corporate procedures and large hierarchical design teams in one case resulted in overly stringent specifications, which effectively stifled innovation.
- Corporate design procedures and ideologies were beneficial when management achieved a non-restrictive design atmosphere.
- Academic stage models of the design process are not followed in practice. "Most industrial design seems to be a series of relatively unstructured activities, which eventually (and often through a series of costly and time-consuming iterations) result in a designed product."
- The data do not support the notion that designers divide and conquer difficult design problems or decompose goals into subgoals.

The authors conclude from this study that "process aids in conceptual design are difficult to identify." Furthermore, "preparing designers to be purpose-oriented, tolerant of ambiguity, capable of working with others, and appreciative of *soft* data might help improve design performance."

This methodology provided the researchers with a systematic and comprehensive framework for gathering, organizing, and analyzing real-world data. The data were used to identify and characterize design decisions and examine both positive and negative effects of decisions made during the design process. The resultant models, the project timeline scenarios, highlight significant information about the contextual and temporal aspects of design.

c. Petroski

Petroski [Ref. 23], from the Department of Civil Engineering at Duke, is interested in applying knowledge of past design failures to the design decision process of current design projects. Typically, the design decision process is influenced by experience from and knowledge of past design successes. Petroski, however, feels that knowledge of design decisions that led to failures is essential to understand the design process more thoroughly and to successfully avoid making similar errors.

The focus of the study reported is bridge design. Petroski analyzes the history of bridge design to identify design decisions concerning determinations such as choice of material or design, process. He provides illustrations of specific examples of situations in which the lack of knowledge about previous design decisions led to the design of subsequent bridges that failed.

Petroski investigates historical examples of design failures to understand the design decision process of a specific engineering domain in a very informal manner. This study illustrates the value of historical case studies as rich sources of data for developing models of design decision processes.

d. Promisel, Hartel, Kaplan, Marcus, and Whittenburg

Promisel, Hartel, Kaplan, Marcus and Whittenburg [Ref. 24] of the Systems Research Laboratory at the US Army Research Institute for the Behavioral and Social Sciences, conducted case studies of the development of four weapons systems (the STINGER, Multiple Launch Rocket System, BLACK HAWK, and M1 Fault Detection and Isolation Subsystems). The specific focus of this research was to assess the extent to which human factor issues were considered throughout the development process of each weapon system.

The methodology used during this study was called *reverse engineering*. This approach consists of

- Defining and describing the system
- Reviewing requirements documents and determining how system performance was specified
- Analyzing test and evaluation data and comparing the data to performance criteria
- Identifying problem areas in system performance
- Examining human factors, manpower, personnel, and training factors for their effect on problematic aspects of system performance
- Reviewing the weapon system acquisition process to identify features that contributed to human factors issues.

To analyze the wealth of life cycle data, the researchers developed a matrix that relates descriptions of the primary activities of the system development process, functions within the weapon system acquisition process, and acquisition process milestones. Within this structure, they were able to "identify causal factors contributing to [the human factors] deficiencies" that were found. The matrix is a general framework that describes the weapon system acquisition process. During this study, it was used to synthesize the data from the four case studies to determine how the weapon system acquisition process could be improved.

This research illustrates the manner in which data can be systematically extracted from case studies and synthesized into a general framework to study aspects of the design process (or, in this case, the weapon system acquisition process).

2. Strengths and Weaknesses of the Approach

a. Strengths

- Allows researchers to examine real-world practices. [Ref. 22]
- Produces information that could improve the likelihood of design success in other design activities. [Ref. 22]
- "Merges advantages of the think-aloud method with a definitive set of broad-based and specific questions concerning the various elements and aspects of a successful real world design which spans the life course of the particular design object." [Ref. 22]
- "Interviews illustrate the difficulties designers face." [Ref. 22]
- "This method allows for the uncovering of a clear portrayal of the various elements of design projects." [Ref. 22]
- "The method works best with a large number of cases, and may be a useful design project characterization since it does show changes over time." [Ref. 22]
- The resultant models depict relationships between the diverse elements of the design decision process.

b. Weaknesses

- "In this retrospective or historical research, information is gathered in the present about projects which have finished. As the events can never be repeated, the researcher has to rely on documented evidence and the memories of those involved during the project. Memories can be unreliable and there is always the tendency to modify and dramatize the events of the past, in other words, the quality of the data is often poor. Not surprisingly, case histories often tend to adopt a specific viewpoint and, because of the way the results are structured, give the impression that the design process was extremely well ordered and logical." [Ref. 17]
- Testing hypotheses using retrospective case studies is very difficult. [Ref. 22]
- Some designers are unable to recount how a new product was invented. [Ref. 22]

- "With retrospective histories, designers only recall major or critical events, and not necessarily what transpired to give rise to them...Designers cannot remember all the considerations in design decisions; at best, they can only tell you what was the decision." [Ref. 22]
- A strong element of subjectivity exists in the interviewing process. [Ref. 21]
- It is difficult to verbalize reasoning that is spatial in nature or that involves visualization of the working of the system. [Ref. 21]

D. KNOWLEDGE REPRESENTATION

Knowledge representation techniques, developed in response to an increasingly high level of interest in encoding and manipulating domain-specific expertise (especially in the domain of engineering design), are invaluable for studying design at both individual and organizational levels of activity. This section reviews the manner in which knowledge representation schemas enrich understanding of organizational level design decision processes.

The purpose of knowledge representation schemas is to capture knowledge (information with an understanding of how it may be applied) in a form that can be processed by a machine. This is a particularly challenging quest for the engineering domain as design data at any point during the product life cycle are typically characterized as follows:

- Complex (many specified and unspecified relationships among design objects, attributes, and relationships)
- Incomplete (Any portion of the design at any point may be only partially described.)
- Inconsistent (Attributes, relationships, and objects may contradict one another on different levels; there may be multiple representations of the same object or component.)
- Ambiguous (Attributes, relationships, and objects may be created with much implicit information that is never explicitly included in the product design definition.)
- Hierarchical (The artifact and components of the artifact are described at many different levels of abstraction, each of which may or may not be complete and consistent with one another.)
- Dynamic (changes over time).

Furthermore, engineering design data appears in a myriad of forms, including parametric, tabular, geometrical, heuristic, matrix, and textual. Engineering design data (data describing the final product and the requisite knowledge used to create it) are fundamentally different from the traditional types of data handled by a computer, such as business data. (Details of this difference are given in the accompanying report, *Managing Engineering Design Information* [Ref. 11].)

A simplified view of the design process is necessary to begin to grapple with the knowledge representation problem posed by engineering design. A description of a basic structure of design suggested by Lindhult is fairly representative of those shared by a number of design researchers [Ref. 25]:

> The design process can be viewed simplistically as comprising the following series of steps:
>
> Problem Definition
> Conceptual Design
> Design Development
> Design Documentation
> Construction and Evaluation
>
> The entire design process is a series of iterative cycles composed of dissimilar activities which range from intuitive leaps to complex technical calculations. Within each of the above steps, information is analyzed and synthesized by the designer and a physical form begins to evolve.

Frameworks such as this provide the basis necessary to apply Newell & Simon's information processing theory of human problem solving to the task of engineering design. Newell and Simon's theory of information processing describes a problem in terms of *states* . The solution to a problem is achieved by the progressive application of *operators*, which transform one problem state into a different state [Ref. 7]. This approach requires an implementation of a task environment (a search space), which is a formal specification of the knowledge needed to solve a problem (or, in this case, design an artifact). A knowledge representation schema, a domain-independent generalized strategy for encoding knowledge, is used to model a particular task environment. Through this method, specific implementations of schemas will contain domain-specific knowledge.

1. Representative Research Studies

The following projects describe different approaches, currently under development, for building representations of task environments. The resulting design spaces are useful models of design decision structures.

a. Kurumatani and Yoshikawa

At the University of Tokyo, Kurumatani and Yoshikawa [Ref. 26] are developing a methodology for modeling knowledge of design objects and processes. This methodology is based on a formal, axiomatic theory of design, *General Design Theory*, proposed by Yoshikawa. General Design Theory provides axioms for characterizing human design activity. From these axioms, the following assertions regarding the representation of design knowledge are derived:

- Any entity can be described by its properties, especially by its attributes.
- Any entity is treated as being on equal terms with other entities--all of the entities should be described in the same way without assuming any absolute hierarchy of entities.
- Design process can be formalized as the operation of abstract concepts. [Ref. 26]

The authors propose a schema based on the General Design Theory for representing design objects and design processes. In this schema, design objects are characterized by their properties and structure (both internal and external). This provides the means for representing the function, attributes, and relationships to other objects. With this schema, a machine can be defined as a network of objects.

Design processes are defined as processes "in which the design object is detailized by making intersections of abstract concepts." Design processes are a series of transformations of design objects during which the the design object concepts become increasingly refined. These transformations are enabled by access to information belonging to the design objects. This view of design suggests "the possibility that a design process can be explained as the alternate actions of two operators to the design object." [Ref. 26]

This schema is being implemented in a frame-based system by the authors. Because it is based on a theoretic model of design, yet provides a practical approach for representing design knowledge symbolically, the schema is especially interesting.

b. Kalay, Swerdloff, and Harfmann

Kalay, Swerdloff, and Harfmann [Ref. 26] are developing and implementing "fundamental paradigms of design as a computable process" at the State University of New York (SUNY) at Buffalo. The focus of this research is the exploration of the potential role of computers as design partners, rather than merely design tools, to increase the flexibility and effectiveness of design processes. The basic premise underlying the paradigms is that a design process is a search for a "physical or organizational scheme which when realized will achieve certain goals and abide by certain constraints." To experiment with this concept, the authors are "providing computers with knowledge similar to that of designers stored in the form of performance, goals, and design plans." [Ref. 27]

The basis for the research is Newell and Simon's state/transition model of problem-solving (see Section D.1), in which states represent design goals in various levels of abstraction.

> A design goal is a "context dependent constraint which defines conditions that candidate solutions must meet." Goals are organized in a goal hierarchy. "Transitions represent the means for choosing and achieving goals." Transitions between goals are achieved under the control of an overall design plan, portions of which are carried out by the designer and the system. [Ref. 27]

The authors have implemented the goal hierarchy and a design process control mechanism in Prolog, and goals are represented in frames. These structures contain descriptive knowledge (constraints) and procedural knowledge (weightings for preferred solutions).

This computational paradigm of design is unique because it allows the designer to determine dynamically which tasks will be performed (which decisions will be made) by the system and which will be made by the designer. The structure of the decisions (the goal hierarchy) and knowledge about design (the content of the goal frames) are maintained by the system. The actual execution of the design decision process is controlled by the designer. The authors suggest that this design paradigm "is applicable to decision-making processes of many kinds." Theoretically, the knowledge base (which currently contains architectural engineering expertise) can be populated with any domain-specific knowledge.

c. McCall

McCall [Ref. 28] is developing a design method called the Procedurally Hierarchical Issue-Based Information System (PHIBIS) method at the University of Colorado at Boulder. PHIBIS is based on the *Issue-Serve Systems* theory of design, which views the design process as an information seeking process. According to this theory, the act of designing is "an attempt to devise an appropriate plan for something to be built or implemented." Models of design processes are thus *quasihierarchies* of questions (issues) that arise during the design project and the *serve relationships* that are developed among the issues. Serve relationships describe dependencies among the issues.

The goal of the PHIBIS method is to describe and improve design processes. Design processes are described by means of representations that "account for the full spectrum of graphic, mathematical, and verbal information processes which occur in design." Information processes are considered paramount during design activity to answer the questions that may arise.

The PHIBIS method addresses improvements to design processes in two respects. First, it provides the means to document design issues for communication among project members. This mechanism consists of knowledge bases for structuring individual issues, positions, arguments, resolutions, explanations, and comments and for structuring the serve relationships among issues. Second, it "uses strategies for raising important design issues." These strategies consist of procedures for systematically structuring the design process.

Theoretically, the PHIBIS method can be implemented without computers. After analyzing an attempt to manually implement this method in 1979, however, the author concluded that the data base was too large and complex to manipulate manually. As a result, the author developed software (called MICROPOLIS) to implement the PHIBIS method. This implementation is currently under further development and testing at Boulder. Current results from this project indicate that this method

- "Becomes a vehicle for critical discussion among the various parties involved in a design project...
- Provides a vehicle for cumulative growth of discourse about recurring issues in design...
- Provides an opportunity for researchers to see into and study design processes and information...

- Provides a vehicle for dialog between research and practice...
- Allows the designer to lay out the various issues, options, and arguments of a design project in a systematic and orderly manner...
- Manages the complexity and controversy...
- Provides a useful bookkeeping system for tracking the current state of thought and discussion." [Ref. 28]

d. Maher

Maher [Ref. 29] is developing a knowledge-based approach for conceptual design at Carnegie Mellon University. The goal of this research is "to provide a domain independent environment for developing a knowledge-based system for preliminary design synthesis" that is sufficiently expressive for representing complex systems and design expertise and experience.

The approach under development incorporates the concepts of problem decomposition and constraint satisfaction to model design as a search process. The design space (in which the search occurs) consists of design goals, goal solutions, and relationships among goals. This knowledge forms the basis for reasoning about design. Design decisions are represented in the form of knowledge about operators that act on elements of the design space. The author distinguishes two types of design decisions--planning knowledge and design knowledge.

> Planning knowledge includes information on which design goals are relevant to the current situation...Planning knowledge is incorporated in the design process so that the decomposition is refined as the solution proceeds. The rules for ordering the design goals can consider the requirements of the given design problem and the current state of the design solution...
>
> "Design knowledge includes information on which design solutions are feasible for the current situation. The design knowledge is used to guide the selection of solutions for individual goals...The design knowledge is specified by the design in the form of alternative solutions for each goal and constraints on combinations of solutions. [Ref. 29]

This approach is being implemented by the authors in a frame-based system called Engineering Design Synthesis (EDESYN). Design knowledge is encoded in hierarchical frame representations. Both planning knowledge and design knowledge are represented in tree structures, where paths through the trees represent feasible design alternatives. Control is distinct from the knowledge. The search mechanisms make use of the design knowledge represented in the tree structures to make design decisions. Although the implementation is not complete and general conclusions have not been drawn, the following aspects of this research are significant:

- With this approach, the design process is planned dynamically as design proceeds.
- All feasible solutions to the design problem are generated, not just the "optimal" solution.
- The approach (both the knowledge representation scheme and the control mechanism) are thoroughly domain independent.

2. Strengths and Weaknesses of the Approach

a. Strengths

- The techniques under development will provide the means to formalize what is known about engineering design data and knowledge. These formalizations provide the basis for rigorous analyses of engineering design processes.
- Using knowledge representation techniques, investigations into the manner in which humans use knowledge can be conducted. Such investigations may test theories about design procedures, what design decisions are made, how the decisions are made, and the reasons for the decisions.

b. Weaknesses

- "There are two major obstacles to integrating expert systems into the design process. The first problem is that expert systems don't yet handle geometric or spatial models effectively. Thus, current expert systems are limited in their ability to assist in the design of physical forms...The second and most pervasive obstacle is that design does not have a complete set of explicit rules. Much research has and is currently being performed on human problem solving and the design process. However, even when rules are determined which reflect human expertise, much of the information in the knowledge base of a typical expert system is either imprecise, incomplete, or not totally reliable. For this reason, the answer to a question or the advice rendered by an expert system is usually qualified with a *certainty factor*..." [Ref. 25]
- Very little is known concerning the most effective ways to elicit knowledge from human experts. To be truly effective, knowledge elicitation techniques should capture the manner in which an expert encodes and retrieves knowledge of a specific domain. In the past, however, knowledge extracted from human

experts has been unnaturally manipulated to match preconceived structures that typically do not accurately reflect the human expertise.

- There are no known exhaustive methods for testing or validating knowledge representations for completeness and consistency.
- Knowledge representation technology has not yet evolved to a state that can handle all of the peculiarities of design engineering data and knowledge. Much basic research is still required.

III. INDIVIDUAL DESIGN RESEARCH STUDIES

This chapter addresses two general methods for studying the design of a product by an individual: protocol analysis and computational experiments of problem-solving behavior.

A. PROTOCOL ANALYSIS

Protocol analysis is an empirical method for studying problem-solving behavior exhibited by individuals through the analysis of verbal reports (protocols). The method is based on Newell and Simon's information processing theory (see Section II.D). Protocol analysis is a systematic methodology for identifying cognitive processes ("sequences of internal states successively transformed by a series of operators" [Ref. 30]) and revealing the nature of the information stored and accessed by human beings during a particular problem-solving situation. With this information, the manner in which human beings solve problems can be described.

The suppositions that this method is based on include

- Thinking aloud does not alter the sequence of cognitive processing significantly.
- Concurrent verbal and retrospective reports provide a nearly complete record of the sequence of information that is needed during task performance.
- Verbally reported information is as regular and valid as other types of data. [Ref. 30]

To conduct protocol analysis research, a lengthy procedure involving preparation, data collection, and extensive data analysis is typically followed. Preparation involves designing a realistic problem-solving experiment, identifying subjects who have an appropriate level of experience in the problem domain of interest, and training the subjects. The subjects are trained to verbalize their mental processes while performing design activities.

Data collection involves recording all verbalizations made by the subjects in the course of solving a given problem. In some cases, all gestures and other movements (such as eye movements) exhibited by the subjects and all products (both intermediate and final) are filmed. This phase of the experiment produces a deluge of detailed data to be interpreted and analyzed by the researchers.

Prior to data analysis, primitive elements that may constitute a general problem-solving strategy are hypothesized. For example, one set of elements may describe the types of verbalizations that are made during problem solving. Data analysis involves encoding chunks of verbalizations with respect to the predefined elements. Ideally, the encoding process will reveal generalized patterns, in terms of the elements, describing the information processing strategy used to solve the problem. Encoding can be achieved only if the verbal data can be characterized in terms of the predetermined elements.

1. Representative Research Studies

Protocol analysis has been applied rigorously to the study of the engineering design process only recently, although many early design studies made use of recorded verbal data to substantiate hypotheses regarding cognitive aspects of the design decision process. A particularly good example of an early study that made use of recorded verbal data to study selected aspects of the design process was done by Malhotra, Thomas, Carroll, and Miller [Ref. 31]. The research methodology developed for this study can be considered a precursor of the protocol analysis methodology. Two extremely recent studies have rigorously applied protocol analysis to test the validity of the method for design research purposes [Ref. 26] and to develop non-trivial models of the mechanical engineering design process [Ref. 32]. The remainder of this section describes the results from these studies.

a. Malhotra, Thomas, Carroll, and Miller

The focus of the Malhotra, Thomas, Carroll, and Miller study [Ref. 31] was to "identify and characterize important design processes...to attain an understanding of the kinds of aids that can assist the design process." Their research is based on the information processing model described in the preceding paragraphs. Specifically, the authors describe the problem-solving paradigm as follows:

> A problem state is said to exist when a human has a goal but no immediate procedure that will guarantee attainment of the goal. The goal may be a satisfaction to be achieved or a dissatisfaction to be alleviated. Problem-

> solving occurs in moving from a problem state to a non-problem state. In problem-solving, then, a person begins in an initial state, uses transformations that move him from one state to another and ends in a final state. Any of these states and transformations may be well-defined or ill-defined. [Ref. 31]

The researchers point out, however, a significant difference between design and general problem solving:

> In the case of design problems, the person is generally not forced to start from a specific initial state, and although there may be constraints on what may be used, the transformations are usually not limited. In real world design situations the goals are, typically, fuzzy and poorly articulated and cannot be mapped directly into properties of the design. Thus, the exact configuration of the final state is not prescribed. A part of the design process consists of formalizing and refining the design goals into functional requirements that can be matched by properties of design. [Ref. 31]

The authors analyzed verbal protocols recorded during an observational study of a client-designer dialogue to test this paradigm in the context of conceptual design. The results from the analysis of the protocol data suggested a model that illustrates the cyclical nature of early client-designer interactions. According to the results, decisions made during this conceptual phase occur in a "series of cycles; each cycle consisting of a regular succession of states. A state is defined as a portion of the dialogue that is oriented towards a single purpose." The six states identified are listed in Table III-1. Thus, each cycle "consists of introducing some requirements, discussing them, outlining a solution, and elaborating and exploring it."

Table III-1. States in the Client-Designer Dialogue

State	Main Speaker
1. Goal Statement	Client
2. Goal Elaboration	Client and Designer
3. Sub Solution Outline	Designer
4. Sub Solution Elaboration	Designer
5. Sub Solution Explication	Client and Designer
6. Agreement on Sub Solution	Client

From the client-designer dialogue experiment and two other related experiments, the researchers developed a general model of the design process. This model decomposes the design process into three fundamental underlying processes: goal elaboration, design generation, and design evaluation. Goal elaboration corresponds to states 1 and 2. Design generation corresponds to states 3, 4, and 5. Design evaluation corresponds to states 5 and 6. These processes are interacting processes and may occur concurrently.

The Malhotra study is an early attempt to propose a "framework within which specific hypotheses can be empirically tested" [Ref. 31]. In particular, this framework can be used to investigate decision support research issues such as the following:

> To what extent do traditional, fact-oriented information retrieval systems provide substantive support to designers?
>
> What are the advantages and disadvantages of rapid prototyping in terms of quickly seeing alternative solutions, prematurely focusing on initial ideas, etc.?
>
> To what extent are on-line expert systems likely to be of value for different types of design problem and phases of design?
>
> In what ways might current computer-aided design, computer-aided manufacturing, and computer-aided engineering (CAD/CAM/CAE) systems be enhanced, within current technology constraints, to provide facts, fantasies, and feedback?
>
> Is it likely that designers will be confused or dissatisfied by a support system whose role is adapted to the nature and state of their design problem solving?
>
> What other roles can be imagined for a design support system, and when might these roles be invoked? [Ref. 3]

b. Eckersley

Eckersley [Ref. 33] used protocol analysis in a study primarily to determine whether or not it is "an effective method for the controlled observation and experimental analysis of design problem-solving behavior." To validate the efficacy of this method, Eckersley formulated a rather general experiment hypothesis that designers vary significantly in the nature and amount of information processed during problem solving.

This hypothesis was tested by analyzing verbal protocols with respect to predefined verbalization categories. The verbalization categories, or types of statements, are primitive elements that may constitute a problem-solving strategy. The types of statements that the researchers expected to find in the protocols included

- Literal copy statements
- Paraphrased copy statements
- Inferences

- Intentions/plans
- Move statements
- Search statements
- Specific assessments
- General assessments.

With these verbalization categories, the authors attempted to model problem-solving behavior as patterns in the occurrences of each type of statement during the design process. These verbalization categories correspond to the types of information processed during problem solving. An analysis of the protocols, however, revealed no general patterns across all subjects. The author concluded that the lack of consistent verbalization patterns supports the working hypothesis. The analysis also supports an informal hypothesis that stages in problem solving would be evident in the analysis of protocol data.

The author concludes that the study was successful in testing protocol analysis and suggests "much work remains to be done in order to establish protocol analysis as a valid design research tool. The potential for experimentally testing research hypotheses is great, provided larger subject-samples are utilized."

c. Ullman, Dietterich, and Stauffer

Ullman, Dietterich, and Stauffer [Ref. 32] recently completed a two-year study of the mechanical design process using the protocol analysis methodology to examine how experienced mechanical designers solve real design problems. This method provided the researchers with a systematic procedure for generating and analyzing empirical data.

The focus of the analysis of copious amounts of protocol data was to identify relationships between form, function, and design decisi ıs. This led to the development of a model of the design process referred to as the Task-Episode Accumulation Model (TEAM). TEAM "explains many aspects of the design process and it provides significant insights into the the way designs are developed."

The concepts underlying TEAM correspond closely with the Newell and Simon information processing theory [see Section II.D]. TEAM describes a problem space in which design states are transformed by design operators.

> The design state contains all information about the evolving design including problem specifications, additional constraints introduced by the

designer, proposed designs, drawings, calculations, assembly plans, and so on.

Design operators are primitive information processes that modify the design state by performing calculations, creating new proposed designs, evaluating proposed designs, and making decisions to accept or reject proposed designs. TEAM contains ten operators: select, create, simulate, calculate, compare, accept, reject, suspend, patch, and refine. [Ref. 32]

To experiment with the concept of a design state, the authors developed a comprehensive representation scheme for the data used during design and identified data representation requirements. A frame-based approach to data representation satisfies these requirements.

In the TEAM model, operators are grouped into meaningful sequences, called episodes, each of which addresses a low-level goal. Heuristic rules guide the decision-making process with respect to the use of operators within an episode. An examination of the episodes reveals design problem-solving strategies used by the subjects. These strategies describe the manner in which a present state of the design was transformed to meet design goals. Strategies exhibited by the subjects include

- "Designers often pursued a single conceptual design both at the level of the overall design problem and at the level of individual subproblems.
- Designers used notes and drawings for understanding and analyzing the problem, not just to record final design decisions.
- Designers progressed from systematic to opportunistic behavior as the design evolved.
- Designers did not always conduct balanced development but sometimes pursued a problem in a depth-first manner.
- Designers sometimes repeated previous efforts in solving the problem.
- Form and function are interrelated in the design process.
- Designers based many decisions on qualitative rather than quantitative reasoning during all phases of design.
- Knowledge controls the design processes.
- Designers made simulations as an aid to understanding problems and evaluating solutions.
- Designers usually found satisfactory solutions rather than optimal solutions." [Ref. 32]

The importance of the TEAM model is that in addition to explaining "the design process to the level of individual utterances in the protocol data," [Ref. 32] it provides many new insights into the design problem-solving behavior of individual designers. The authors suggest a number of implications these results have on the development of design aids. For instance:

- "Existing CAD tools are addressing primarily the detail design tasks, because CAD tools are only capable of representing the geometric design state when it is refined to a concrete or near-concrete level." [Ref. 32]
- Users of CAD tools would benefit from constraint management assistance.
- "Existing artificial intelligence models of design are still rather simplistic and inflexible." [Ref. 32]

TEAM will be refined and augmented with results from a recently begun three-year project to continue the examination of the design process and "to design and implement a design history tool."

2. Strengths and Weaknesses of the Approach

The following strength statements made by a variety of researchers who have studied or made use of the protocol analysis methodology provide support for the potential of protocol analysis for studying the individual human problem-solving process. These statements also suggest that this methodology is still under development; results suggested by protocol analysis studies must be used with caution.

a. Strengths

- "Since thought is not a directly observable activity, introspective and retrospective accounts of human thought have rightly been regarded as unreliable data for scientific enquiry. However,...under controlled conditions, individuals...can reveal a remarkably accurate picture of their cognitive processes while engaged in problem solving....Protocol analysis offers the community of design scientists...a potentially effective method for the controlled observation and experimental analysis of design problem-solving behavior." [Ref. 33]
- "The power of this approach lies in its richness of data. Fragmentary glimpses of complex processes provide more information about the processes than simply the outcome." [Ref. 34]

- The resulting model can be used to guide research and as a baseline for refined models. The method can be used to test models (i.e., which parts are correct, which need to be refined or replaced). [Ref. 34]
- "The potential for experimentally testing research hypotheses is great, provided larger subject-samples are utilized." [Ref. 33]
- Introspection is useful for discovery purposes. [Ref. 30]
- This method is useful for eliciting much valuable information about all aspects of design activity that designers have difficulty expressing.
- "Educationally, protocol analysis could be of potential use as a diagnostic tool, or as an instrument to show students the 'form' of their problem-solving, of which they may be singularly unconscious." [Ref. 33]

b. Weaknesses

- The suitability of the subject's verbalizations as scientific data is debatable. [Ref. 30]
- "The process of verbalization disrupts thought processes." [Ref. 21] "The requirements to 'think out loud' tend to slow subjects down, [although] research has shown that this does not affect the order or content of their problem solving steps." [Ref. 32]
- "Verbal protocols...cannot record what happens during incubation, when the subject 'mulls over' the problem for a few days and thinks up ideas." [Ref. 32]
- Encoding behavior into data is subjective and prone to bias. Different interpreters will arrive at an interpretation that is consistent with the investigator's particular theoretical orientation. [Ref. 30]
- The theoretical presuppositions are embedded in the encoding process. [Ref. 30]
- The investigators must be concerned with methodological questions about data collection. [Ref. 30]
- Protocols will always be incomplete. Processes occur that the subject cannot or does not report. Furthermore, the subject can only report a linear sequence of thoughts, one thought at a time. Unstated thoughts regarding form, function, and process must be inferred by the investigators.
- It is difficult to study the entire design process in one session. The size of the design problem requires several sessions. After two to three hours fatigue sets in. [Ref. 32].

- "Real-time protocol analysis has limitations based on the volume of information which must be collected and sorted. The integrated visual, spatial, and verbal nature of the knowledge and decisions made by a group of individuals is often inadequately represented by this mode of data collection." [Ref. 21]
- It is best suited to studying subjects solving problems by themselves. Engineers, however, often design in teams or at least pass their problems around for others to review. [Ullman, et al.] could not think of any practical way of accommodating this aspect of design in the present study." [Ref. 32]

B. COMPUTATIONAL EXPERIMENTS OF PROBLEM-SOLVING BEHAVIOR

Many design research programs focus on investigating theories and hypotheses regarding human design problem solving by conducting empirical experiments. These experiments, both laboratory and computational, are purposely designed and controlled to generate empirical evidence of cognitive design decision activity at the level of the individual. By analyzing the resulting data and identifying general patterns, the researchers are able to substantiate, refine, or refute research hypotheses.

The resulting data are reduced and analyzed statistically. Analysis results are used to test the original hypothesized models of design activity and set forth new ideas about design problem-solving behavior.

Computational experiments are an alternative approach to traditional laboratory methods for testing models of the design process. The purpose of computational experiments is similar in intent to laboratory experiments. After conceptualizing a model of a specific aspect of cognitive problem-solving activity, the model is implemented in software. The resulting computational program is evaluated to validate the original hypotheses and identify weaknesses of the model. The value of the computer as a research tool used in this context is described by Gasparski, et al. [Ref. 35]:

> Development of computer science has greatly contributed to the development of research on the processes of solving design problems. Analysis of the very design problems became an alternative to drawing conclusions from observation of patterns of the design process.

Furthermore, the evolution of artificial intelligence techniques that aim to render non-deterministic processes computable, has contributed significantly to the arsenal of viable techniques for testing models of the design problem-solving process.

An important distinction exists between programs that design and programs to test theories about how people design artifacts. The former are considered computational *aids* for the design process. They typically address specific segments of the detailed phases of design. The tasks that they perform involve routine or mechanistic design decisions and are very discipline specific. The latter, however, are computational *models* of design processes. The usual focus of these programs is the conceptual phase of design, characterized by synthesis tasks that require innovative solutions to complex or ill-defined design decisions.

The next section describes three experiments to test theories of human design problem-solving activity by implementing computational models of specific aspects of the design decision process.

1. Representative Research Studies

The design research literature contains a number of interesting reports of computational experiments aimed at gathering empirical evidence to refine models of various aspects of the design process at the level of individual activity. Results from these experiments have contributed significantly toward a deeper understanding of cognitive reasoning processes underlying design problem-solving behavior.

The three research experiments described in this section form a representational sampling of computational experiments that have been and are being conducted. The design decision process models that have resulted from these three projects provide evidence of

- The manner in which designers use knowledge and skills to produce a novel design
- The nature of operational knowledge and goal specifications necessary to make correct design decisions
- The role of episodic memory and analogical reasoning
- Stages of reasoning used during design
- The manner in which design knowledge is formed and design experience is acquired and formalized
- Aspects of the design process that should be subjected to analysis

- Requirements for generic processes of invention
- The role of rules of invention and creativity.

a. Dyer and Flowers

Dyer and Flowers [Ref. 36] are exploring applications of artificial intelligence (AI) to design at the University of California at Los Angeles. They are particularly interested in exploring the cognitive skills of mechanical design engineers. With an understanding of human problem-solving strategies, they hope to create AI systems that will aid the design process. Their research reported in this study addresses the question "of whether and to what extent, processes of creative thought can be encoded into a computer so that the computer can be said to have invented something on its own." [Ref. 36]

The research is based on Newell and Simon's information processing model of problem solving [see Section II.D]. The inventive aspect of the mechanical design process

> is viewed as a search through a large space of states representing objects or ideas. Movement from one state to another is accomplished by the application of an operator. In our case, the state space consists of object designs and the operators are 'creativity rules' or rule schemas which modify or combine existing objects to yield new designs. [Ref. 36]

The rule schemas direct the inventive design decision process. The purpose of the rules schemas is to embody the manner in which a designer uses knowledge and skills to produce a novel design.

To test the feasibility of applying AI to design with this paradigm, the authors attempted to automate the invention of "a novel version of a familiar device--i.e., the door." [Ref. 36] Heuristic rules of creativity were developed using informal introspective protocols (the authors documented what they believed they were doing cognitively while inventing a novel device). These rules were implemented in an expert system (the Intelligent Design Invention System).

The following conclusions were drawn from the results of the computational experiment:

- Problem solving is central to invention.
- Operational knowledge (i.e., common sense knowledge) is necessary to make correct decisions.

- Functional and goal specifications are necessary to make correct design decisions.
- The ability to distinguish novel solutions from routine solutions is necessary to make correct design decisions.
- Episodic memory and analogical reasoning is crucial for creative problem-solving (for instance it is important to be able to "take an object from a completely different domain and apply it to the current task domain, altering it as needed"). [Ref. 36]

The design decision process model that resulted from this research is in the form of a collection of expert system rule schemas. These rule schemas provide the expert system with necessary information and guidelines to make design decisions during attempts to invent some novel device.

b. Findler

Findler [Ref. 5], at the State University of New York (SUNY) at Buffalo, is studying the role of analogical reasoning in problem solving by computers with attention directed towards design processes. He views design as an ill-structured problem that is difficult to solve by any prescribed algorithm. To study the role of analogical reasoning in the design process certain assumptions about the design process are made. Specifically:

- Each design problem is describable as an (ordered) collection of certain, possibly overlapping, fundamental features.
- Solutions are associated with respective problems in a well-defined, deterministic manner....The features of the problems are identifiable and are strongly enough correlated with the solutions so that the latter can be directly derived from the former.
- In the task domains of interest to us, similar problems have similar solutions.
- When two problems have similar solutions, the features present in one problem but not in the other are likely to be of lesser importance. In turn, features shared by problems which have similar solutions are likely to be important. [Ref. 5]

Findler conducted several computational experiments to identify "what information should be extracted from raw experience consisting of descriptions of problems and solutions, and how this information can then be used in determining solutions to new problems." [Ref. 5] These experiments consisted of implementing two different yet mutually supportive models of analogical reasoning mechanisms:

Contributive model: A solution to the problem is constructed incrementally by (1) generating transformation functions between features of previous problems and solutions, and(2) applying the transformation functions to the current problem to identify a solution. [Figure III-1(a)]

Hierarchical model: The hierarchical relationships between problem features are accounted for in this model by (1) finding transformation functions between features of a relevant previous problem and features of the current problem, and (2) applying those transformation functions to the solution of the most relevant previous problem to obtain a solution to the current problem. [Figure III-1(b)]

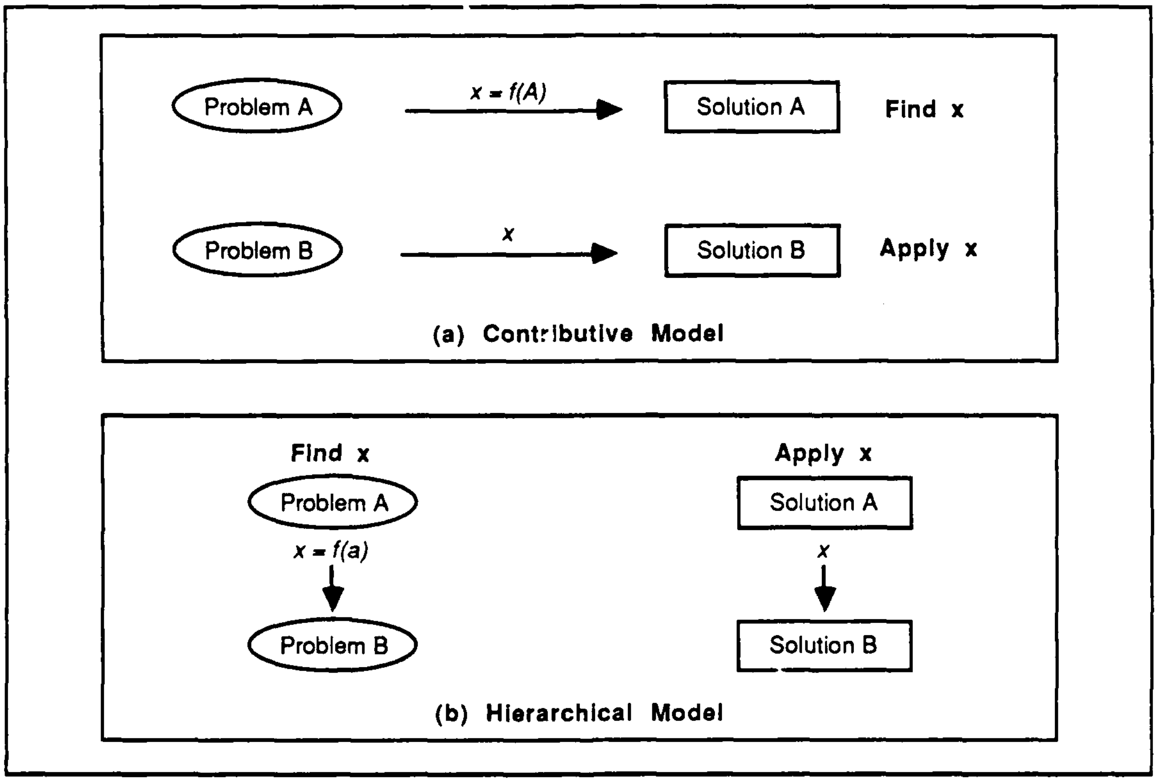

Figure III-1. Findler's Models of Analogical Reasoning

These experiments resulted in two general conclusions:

- The processes of analogical reasoning are a useful and general component of design problem solving.

- The computational procedures implemented in this study effectively transform raw experience in problem solving into a viable knowledge base to support design decisionmaking.

This research is particularly interesting because it attempts to describe analogical reasoning mechanisms that collect and process experiential information that designers use to make design decisions. It provides models of cognitive strategies that guide the search for solutions during design. These models form a framework for exploring both how experiential knowledge is used during design and the extent to which learning is an integral component of the design process.

c. Green and Brown

As part of ongoing research into routine design, Green and Brown [Ref. 37] at Worcester Polytechnic Institute are investigating "knowledge and problem-solving behavior used during routine design." The background for this project is explained by the authors:

> Brown and Chandrasekaran have proposed that knowledge about routine design is distributed throughout a tightly organized, hierarchical structure. Problem-solving activity occurs as control passes among the pieces of knowledge in this hierarchy. This hierarchy represents a very "compiled" form of the knowledge as all the alternatives are captured in the structure by alternative design plans, or by simple choices in design knowledge.

This study focuses on strategies for "compiling" or generating a specific type of design knowledge, constraint knowledge. The specific question being addressed is how a mechanical design engineer can determine the content of a constraint with respect to how well previously designed subcomponents fit together. The generation of constraint knowledge of this type requires spatial reasoning.

The authors developed a four-stage, sequential yet continuous, model of the spatial reasoning process to explore the manner in which constraint knowledge is formed. During each stage, a unique set of decisions must be made about how subcomponents may fit together. The stages and examples of corresponding decisions are shown in Table III-2.

The last two stages of this model have been implemented and tested against a problem space representing a very simplistic class of objects. Early results from this implementation confirm the authors' suspicion that the spatial reasoning process is quite complex. Limitations in the current implementation suggest necessary extensions to the model to "cover more complex and realistic objects." As a result of this implementation,

Table III-2. Stages in the Spatial Reasoning Process

Stage	Decisions
Grouping	Which features of the object are extraneous to the fit problem and which are important? How should relevant features be clustered?
Orientation	Which surfaces of the object are likely candidates for matching? Should the object be rotated? Should the surface be rotated?
Matching	What information about the features in each cluster should be retrieved? Which clusters of features on one object match clusters of features on the other?
Confirmation	Are the paired features compatible? Was a fit successful?

the authors have identified several important types of knowledge and are confident that the proposed model of the spatial reasoning process is tenable.

2. Strengths and Weaknesses of the Approach

a. Strengths

- Computational experiments can result in a wealth of raw data that serves as direct evidence to support models of design decision processes at the level of individual activity.
- The resultant design models attempt to describe how people actually design as opposed to describing how people should design.
- In addition to attempting to describe individual design decision situations, the resultant models also attempt to provide an explanation of the manner in which design is accomplished.

b. Weaknesses

- Theoretical principles underlying a general *science of design* have yet to be postulated and accepted by the engineering design research community at large. Thus, empirical experiments of design problem solving, while undoubtedly contributing to the development of design principles, are not based on a universal framework of understanding.
- Computational experiments do not test or consider all types of problems engineers may expect to encounter during engineering design.

- The experiments examine the design process from a single perspective.
- Reasoning strategies under investigation are fixed in advance. [Ref. 15]
- The experimental hypotheses under investigation are not tested in a real world engineering setting. The ways in which a subject solves a design problem in a laboratory, or a machine is programmed to solve a design problem, are not necessarily related to the manner in which engineering design actually precedes.

IV. OBSERVATIONS

A. DIVERSE MOTIVATIONS

A diverse number of motivations drive the study of the design process from both theoretical and practical points of view. For example, there are pockets of investigators throughout the world seeking to

- Establish a science of design
- Examine underlying mental processes and cognitive strategies followed during a problem-solving activity
- Understand the industrial and economic implications of engineering design processes
- Develop techniques that could help designers in certain stages of their work, such as brainstorming, synectics,[1] value analysis, morphology, and lateral thinking
- Develop "systematic procedures to guide the design process" (such as the German VDI-Richtlinien) [Ref. 4]
- Capture design experience by means of expert systems, etc. [Ref. 4]
- Develop improved methods for teaching design.

The abstracts of these surveys are included in the annotated bibliography. Anyone interested in engineering design research should examine these papers in detail before initiating related work.

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1 Synectics is the study of creative processes, especially as applied to the solution of problems by a group of diverse individuals. Synectics comes from the Greek word meaning the joining together of different and apparently irrelevant elements.

B. COMMON THEMES

Many common themes underlie the research reported. These commonalities include

- The engineering design problem is an "ill-structured" problem," and thus difficult to solve by any set algorithm." [Ref. 5]
- Design problems are hierarchical and can be decomposed into subproblems.
- Design is both a creative and analytical process.
- Design is a dynamic and iterative process.
- Design problem-solving behavior involves analogical reasoning.
- "The nature of designing requires an interdisciplinary approach." [Ref. 6]
- Design is both a technical and behavioral process; it cannot be studied as though it were one and not the other. [Ref. 7]
- Although a number of attempts have been made to define engineering design, none has been completely successful. [Ref. 8]
- Designers do not attempt to find optimum solutions, rather they attempt to find solutions that work ("satisfice").
- "Many researchers opt for a systems approach." [Ref. 9]
- Design decisions are usually not independent.
- There is no interdisciplinary "language of design." [Ref. 6]
- There are few, if any, automated aids for conceptual design. Most design aids are applicable during detail design.

C. COMMON DEFINITIONS

Most of the definitions of the engineering design process suggested by individual researchers closely match those of the Accreditation Board of Engineering and Technology (ABET). Engineering design is described by ABET as

> the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. [Ref. 8]

D. SUMMARY

This report has reviewed six approaches that have been used by the engineering design research community to examine the design decision process. These approaches yield valuable information about design processes. The approaches, however, result in significantly different types of design decision process information. Table IV-1 is a summary of the types of design decision process information that is typically produced.

Table IV-1. Design Decision Process Information

Approach	Design Decision Process Model
Systems Analysis	Hierarchical, systematic diagrams of the activities, information flows, and influences characterizing a typical engineering design process
Participant Observation	Quantitative (graphs, etc.) and qualitative (narratives, etc.) descriptions of the activities of a particular design project
Retrospective Analysis	High-level frameworks describing the major drivers and decision points of past engineering projects
Knowledge Representation	Formal representations of design decision structures
Protocol Analysis	High-level frameworks that describe the basic components of cognitive activity associated with design problem solving
Computational Experiments	Executable models of problem-solving behavior

The research results are all considered *models* of the design decision process. Although the natures of the models listed in Table IV-1 are quite distinct, each representation serves as a tool for considering the design process problem. Because none of the models considers all aspects of the engineering design decision process, a combination of approaches is required to study design processes in their entirety. As this paper illustrates, the engineering design research community is exploring the application of different types of methodologies to advance its understanding of the design decision process. Motivation for this work is well stated by Simon:

> There are no more promising or important targets for basic scientific research than understanding how human minds, with and without the help of computers, solve problems and make decisions effectively, and improving our problem-solving and decision-making capabilities. [Ref. 10]

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Appendix A

ANNOTATED BIBLIOGRAPHY

ANNOTATED BIBLIOGRAPHY

This bibliography contains three sections. Section A lists surveys of the engineering design research literature. Section B lists articles that describe engineering design research projects. These projects are organized in the following categories:

Methods to model organizational design decision processes

- Systems analysis
- Participant observation
- Retrospective analysis
- Expert system knowledge representation.

Methods to model individual design decision processes

- Protocol analysis
- Laboratory and computational experiments.

Section C lists books and articles that directly relate to or contribute to the understanding of the research studies described in Section B.

A. REVIEWS OF DESIGN RESEARCH

Eder, Ernst., "Design Science--A Survey of Some Approaches," *Proceedings of the 1987 ASEE Annual Conference.*

ABSTRACT: "The conditions under which a body of knowledge can be labelled a science are surveyed. It is shown that if engineering design can be studied in its widest context a 'design science' can be generated. This conclusion is based on the definition as follows:

Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the requirements of mankind.

In order to establish a scientific theory of design, the following aspects need to be studied and covered:

- The designer--characteristics, working methods, use of information, etc.
- The activity--structure, systematic aspects and creativity, factors affecting design processes, etc.
- The object to be designed--nature, properties, processes to be performed, necessary parts, abstractions and models, life stages, representations, evaluations and decisions, etc.
- The context in which engineering design takes place, and
- The context of use of the resulting technical system.

Current developments in attempts to create design science are briefly described. In particular, reference is made to relevant developments in

- Germany (schools of Prof. Pahl and Beitz, and Prof. Roth, social context by Prof. Ropoh., and the recommendations issued by Verein Deutscher Ingenieure),
- Poland (schools of Dr. Gasparski, and Dr. Dietrych),
- Japan (schools of Prof. Yoshikawa),
- Switzerland (school of Dr. Hubka), and
- England (Design Research Society, and various fragments).

Design science is brought into connection with necessary developments of some computer aids, expert systems, and concepts of CAD, CAD/CAM, and CIM."

Finkelstein, L. and A.C.W. Finkelstein, "Review of Design Methodology," *IEE Proceedings*, Vol. 130, Pt. A, No. 4, June 1983, pp. 213-222.

ABSTRACT: "This paper surveys design methodology, the science of methods of design. It discusses the aims of design methodology as well as objections to it. The various sources of design methodology are reviewed. The nature and structure of the design process are outlined. An organized presentation is given of methods of design concept generation. Finally the evaluation and decision steps in design are briefly analyzed. In conclusion the authors state their contention that design methodology is a useful contribution to design."

Gasparski, W.W., S.A. Gregory, R. Foque, and A. Strzalecki, "Contemporary History of Design Science," *Paper for XVI International Congress of the History of Science*, 26 August-3 September 1981, Bucharest, Romania.

Hight, T.K., L. Ginszauskas, and D. MacLean, "Investigation into the Methods Students Use to Solve Mechanical Design Problems," *Proceedings of the International Conference on Engineering Design*, August 1987, Boston, Massachusetts, pp. 888-897.

Prior to describing research into the manner in which students approach design problem-solving, the author summarizes past research endeavors that have resulted in significant contributions to the study of engineering design, regardless of design discipline.

Lera, Sebastian., "Synopsis of Some Recent Published Studies of the Design Process and Designer Behavior," *Design Studies*, Vol. 4, No. 2, April 1983, pp. 133-140.

This series of synopses describes research into the problem solving behavior exhibited by design engineers (architecture, urban planning, civil engineering). Results from the following projects are reviewed:

Research	Institution	Techniques	Published
Eastman	Carnegie Mellon	Lab Observation	1970
Foz	MIT	Lab Observation	1972
Cornforth	Royal College of Art	Protocol Analysis and Repertory Grid	1976
Thomas and Carroll •	IBM Research Lab	Lab Experiments	1975
Simmonds	Oxford Polytechnic	Lab Observation	1980
Lera	Royal College of Art	Scaling Method	1980
Krauss and Myer	MIT	Case Study	1970
Hykin	Imperial College	11 Case Studies	1972
Mallen and Goumain	Royal College of Art	Repertory Grid and Field Studies	1973
Willey and Yeomans	University of Liverpool	Case Studies	1976
Wang	Portsmouth Polytechnic	Participant/Observation	1978
Bessant and McMahon		Participant/Observation	1977
Darke	University of Sheffield	Interviews	1979
Al, Wareh and Murta	University of Sheffield	Interviews	1979
Murtha	University of Wisconsin	Design Exercises	1973
Thompson and Wood	PSA, Royal College of Art	Design Exercise	1975

Libardi, Eugene C., John R. Dixon, and Melvin K. Simmons, "Computer Environments for the Design of Mechanical Assemblies: A Research Review," *Received from the authors*.

The authors describe significant results and interesting ideas from recent "research in artificial intelligence and mechanical engineering that is relevant to aspects of conceptual design environments for mechanical systems and assemblies." This review is organized in categories corresponding to five basic requirements (defined by the authors) of a conceptual design aid for mechanical systems. The categories are

- Methods for representing top-down design and multiple viewpoints
- Methods for representing and using functional knowledge
- Methods for representing spatial relationships

- Methods for maintaining consistency and handling inconsistency among representations
- Methods for providing analysis and other support.

Magee, Kevin, "The Elicitation of Knowledge from Designers," *Design Studies*, Vol. 8, No. 2, April 1987, pp. 62-69.

The author characterizes design activity and describes techniques that may be useful to elicit knowledge about the design activity from engineers. Knowledge elicitation is defined as the process of documenting expert knowledge by means of a dialogue between a knowledge engineer and human expert. The seven techniques reviewed include interviewing, questionnaires, attitude scaling, projective tests, repertory grid, and observation of behavior. For each technique the author identifies advantages and disadvantages. These are summarized as follows:

Technique	Advantages	Disadvantages
Interviewing	Flexibility	Possibility of bias, inconsistencies between what people say they do and what they actually do
Questionnaires	Efficiency, convenience	Inflexible, inconsistencies between what people say they do and what they actually do
Attitude Scaling	Provides a general measure of individual's attitudes toward a subject	Time-consuming, does not provide detailed information
Protective Testing	Overcomes barriers to communication	Validity, reliability, and objectivity of information disputed
Repertory Grid Methods	Provides information about the domain, contentious points, and how the expert categorizes his knowledge	Does not handle complexity very well, limited range of applicability
Protocol Analysis	Results in much valuable and reliable information, information about all aspects of design activity can be elicited. Useful for eliciting information that designers have difficulty expressing	Analysis of data time-consuming, there is no universal way to analyze protocols
Observation of Design Behavior	Useful for eliciting information that designers have difficulty expressing	

The author concludes by suggesting: "more effort should be made to use and improve techniques other than interviewing."

Ostrofsky, Benjamin, *Morphology of Design of Aerospace Systems with Inclusion of Human Factors.*, Final Report under AFOSR Grant No. 77-3148, University of Houston, August 1977, AD A049999.

The research reported in this technical report includes a "review of the literature describing the design decision structure as it relates to the development of aerospace systems as well as identifying the human resource factors relevant to the design structure." An annotated bibliography was prepared as a result of the literature review. Most of the bibliographic entries are from the journal, *Human Factors*.

Schon, D.A. and L.I. Bucciarelli, "Design Theory and Methods--An Interdisciplinary Approach," *Preprints of the Design Theory '88 NSF Grantee Workshop on Design Theory and Methodology*, Troy, NY, June 1988, pp. 2.1.1-2.1.9.

The authors report on the status of current research underway by the members of the Design Theory and Methods Group at MIT. This group is concerned with the nature of design inquiry and designers' knowledge from the perspective of many disciplines: architecture, environmental design, planning and engineering. The questions being addressed by the research are

- What aspects of designing can be made computable?
- What are the properties of a computer assistant useful to designers?

Current research ventures include

Researchers	Focus
Gross, Ervin, Anderson, and Fleisher	Developing "constraint manager," an automated environment that models design as a search within constraints
Purcell	Evaluating computer environments to determine what needs to be done to assist designers
Habraken and Gross	Developing a conceptual framework (concept design games) intended to explore and illuminate important design ideas
Bucciarelli	Studying the design process in situ to explore the character and consequences of the discourse through which design participants communicate with each other
Porter and Schon	Concerned with the experienced phenomena of designing

Tempczyk, Halina, "A Survey of Research and Studies on Design," *Design Studies*, Vol. 7, No. 4, October 1986, pp. 199-215.

The authors draw a number of conclusions from 191 responses to a questionnaire distributed in 1984-85 by the Design Methodology Unit at the Department of Praxeology of the Institute of Philosophy and Sociology of the Polish Academy of Sciences. Information was obtained about various programs in Poland, the USSR, West Germany, the UK, USA, West Berlin, Japan, Australia, China, Czechoslovakia, Canada, Austria, Bulgaria, Holland, Hungary, Italy, and Mexico. The most valuable part of this paper is a comprehensive table of the basic information received from the respondents. Specific studies mentioned in the narrative include

Researcher	Nation	Focus
Yoshikawa	Japan	A general theory of design based on the thinking process
Gregory	UK	Design projects and processes assuming a background of uncertainty. *Collects data from field studies*, lab *observations*, *protocols*, reports, and public statements made by designers
Buge	Canada	Ontological features of artifacts and features characterizing their design
Cross	UK	The epistemological foundations of design knowledge
Jones	UK	A universal humanistic conception of design
Gasparski	Poland	Design knowledge collected from various disciplines
Volkema	USA	The multiplicity of goals in the early phases of strategic planning
Stasiak	Poland	Action, treated as a syndrome of thought processes
Szucs	Hungary	The general meaning of technical culture
Nalimov	USSR	The world as a system of probabilistic concepts
Rubin and Altshuller	USSR	A theory of the development of technical systems
Samuel	Australia	The formulation of goals connected with engineering design
Kulakowska	Poland	Supporting the design process in the information processing aspect
Kerner and Miller	Poland	The information needs of designers
Bonkowics-Sittauer	Poland	Formal descriptions of the design process
Partyka	Poland	Model of the automatic creation of functional schemes of technical objects
Kostov Jungerman	Bulgaria West Berlin	Automating scientific investigations, decisionmaking theory
Tondl	Czechoslovakia	Decisionmaking theory
Wise	USA	Cognitive processes in design decision making

Some observations made by the author include

- Much attention is devoted to problems connected with teaching design and textbooks on design methodology.
- Many researchers are working on the methodology of particular fields and an especially large group are studying engineering design methodology.
- Many researchers opt for a systems approach.
- Many projects are devoted to problems connected with computer-aided actions, mainly teaching and design.
- Many researchers are dealing with problems of decisionmaking as related to design.

Stauffer, L .A. and D.G. Ullman, "A Comparison of the Results of Empirical Studies into the Mechanical Design Process," *Design Studies*, Vol. 9, No. 2, April 1988, pp. 107-114.

Compares six independent studies that investigated the mechanical design process by studying human designers. These studies were each based on empirical data. The studies are listed below.

Study	Goal	Significance
Marples, 1961, Retrospective Analyses	Develop an abstract model of the design process	Describes the design process as a decision tree, a sequence of critical decisions leading from an abstract problem statement to the final specification
Ramstrom and Rhenman, 1965, Retrospective Analyses	Suggest a method of describing and analyzing the progress of an engineering design project	R&R are the first to label design as a problem-solving process. They also consider design a group activity, which in turn interacts with the entire organization and finally with others outside the organization
Lewis, 1981, Retrospective Analyses	Construct an information processing model of component design	
Waldron and Waldron, 1987, Retrospective Analyses	Make observations about design during the conceptual design phase	
Mitroff, 1967, Observation	Add to the understanding of design	Design is both a technical and a behavioral process. Individual behavior is as important as the technical aspects of design
Stauffer & Ullman, Protocol Analyses	Develop a detailed model of the ME design process suitable for intelligent computer tools and for the evaluation of design strategies	The work is based on the information processing model of Newell and Simon, and thus considers problem solving as a transformation of the state of the design through the application of operators

Dimensions for comparing these studies:

- Number of designers working together on a single project
- Of those working on the project, the number used in the study
- The number of cases on which the study is based
- Attention given to designer interaction with other individuals
- The purpose of the design projects
- The types of data gathered.

The six studies led to 44 conclusions describing design performance grouped into 4 categories:

- Algorithmic vs heuristic nature of design
- Parallel vs serial development of solutions
- Technical vs behavioral nature of design
- Dependence vs independence of design on domain knowledge.

The author notes "...serious study in design in general has occurred only in the past 25 years."

B. ENGINEERING DESIGN RESEARCH PROJECTS

1. Methods Used to Model the Organizational Design Decision Process

a. Systems Analysis

Fulton, R.E., "A Framework for Innovation," *Computers in Mechanical Engineering*, March 1987, pp. 26-40.

Fulton, R.E. and Salley, G.C., "IPAD: A Unique Approach to Government/Industry Cooperation for Technology Development and Transfer," *NASA Technical Memorandum 86422*, Langley Research Center, June 1985.

ABSTRACT: "A key element to improved industry productivity is effective management of CAD/CAM information. To stimulate advancements in this area, a unique joint government/industry project designated Integrated Programs for Aerospace-Vehicle Design (IPAD) was carried out from 1971-1984. The goal was to raise aerospace industry productivity through advancement of computer based technology to integrate and manage information involved in the design and manufacturing process. IPAD research was guided by an Industry Technical Advisory Board (ITAB) composed of over 100 representatives from aerospace and computer companies. The project complemented traditional NASA/DoD research to develop aerospace design technology and the Air Force's Integrated Computer-Aided Manufacturing (ICAM) program to advance CAM technology. IPAD had unprecedented industry support and involvement

and served as a unique approach to government/industry cooperation in the development and transfer of advanced technology. This paper summarizes the IPAD project background, approach, accomplishments, industry involvement, technology transfer mechanisms, and lessons learned from the project."

Gartz, P.E., "Avionics Development and Integration System Methods," *IEEE AES Magazine*, June 1987, pp. 2-8.

ABSTRACT: "This paper describes a set of life cycle methods that were developed in 1980 and 1981 and used in the later phases of the 757/767 airplane programs. They have been used as a framework to establish and guide the introduction of a wide use of similar methods for the future avionics of Boeing's next airplane, the 7J7. The methods were designed to improve the communication of the system's requirements, architecture and implementation to a wide group of interested parties--not just the development engineers but also the users, maintainers, customers, and support organizations. A major aspect of these methods is that they were designed to be used for systems in general not just software systems.

This paper describes the background and goals and objectives leading to the need for systems engineering methods, describes the methods, and gives an example of their use. It concludes with remarks on steps taken to introduce methods of this type on a wide scale to support the next Boeing airplane."

Love, Tom, "A Review of the Variables Which Influence the Software Development Process," *General Electric Report TIS 761SP001*, AD #B063727, June 28, 1976.

ABSTRACT: "The software development process is divided into three stages:

1. Task demands
2. Program development process
3. Operating program

The Program Development Process is further divided into four components: Programmer, Computer System, Work Environment, and Software Development System.

Within this framework, recent work in software engineering and psychology are reviewed and discussed. Most of the general papers in the field of software engineering are included in this review."

General Electric Space Division.

b. Participant Observation Studies

Bucciarelli, L.L., "Reflective Practice in Engineering Design," *Design Studies*. Vol. 5, No. 3, July 1984, pp. 185-190.

The author describes research "to develop a better understanding of the design process and to determine how values inform decisions and thus affect the forms of technology that emerge from that process." The method used during this study is called participant/observation. This method reveals "the social as well as technical elements of decisions made in a firm's endeavor to develop and market its wares."

From this study the author has observed:

> "Different participants in the design process have different perceptions of the design...The task of design is...as much a matter of getting different people to share a common perspective, to agree on the most significant issues, and to shape consensus on what must be done next, as it is a matter of concept formation, evaluation of alternatives, costing and sizing..."

School of Engineering, MIT.

Bucciarelli, L.L. and D.S. Schon, "Generic Design Process in Architecture and Engineering: A Dialogue concerning at least Two Design Worlds," *Proceedings of the NSF Workshop on the Study of the Design Process*, February 1987, Oakland, CA, pp. 295-313.

The authors describe their individual theories of how designers design from the points of view of architectural design and engineering design. As stated by the authors:

> "Our purpose has been to explore a perspective on design in both architecture and engineering that sees design as a dynamic process, one in which the designer shapes and imagines, calculates and trades off within a design world which is personal though culturally shared..."

Wallace, K.M., "Studying the Engineering Design Process in Practise," *Proceedings of the 1987 Congress on Planning and Design Theory*, American Society of Mechanical Engineers, Boston, MA., August 1987, pp. 29-34.

The author addresses the fundamental question: How can the performance of design teams be improved? He describes four research methods suitable for studying the engineering design process and presents results from a four-year study of the design process, the Cambridge Project. The research methods described by the author are: case history, direct observation, participant observation, and action research. These are methods for gathering both quantitative and qualitative data. According to the author:

> "All have an important role to play. If design researchers are to discover links and relationships between the different categories of knowledge, they must understand, use, and adapt the research techniques from such diverse fields as

> engineering, sociology, anthropology, psychology, management, economics, and business."

The method adopted for the Cambridge Project was participant observation. The objectives for this study included modeling the design process observed in context. Upon completion of the project, the researchers concluded that

> "from a single investigation, or even a few, it is not reasonable to expect significant general conclusions or guidelines to emerge. But...much can be learned about gathering, verifying, categorizing and analyzing data....With time, as the number of investigations builds up, patterns and insights will undoubtedly emerge. These will be valuable, even if they cannot ever be considered as absolute."

University of Engineering Department, Cambridge.

Wallace, K.M., "Detailed Analysis of an Engineering Design Project," *Proceedings of the International Conference on Engineering Design,* August 1987, Boston, MA, pp. 94-101.

SUMMARY: "To help meet the calls for more effective engineering design in practice better understanding of the engineering design process in industry is needed. Participant observation of engineering design projects and analysis of the field data collected is one possible approach for this. The participant observation of a two-year engineering design project involving 37 people and 2,368 hours of work effort is summarized in this paper. The project is briefly described, and some of the quantitative and qualitative results are discussed with reference to a model."

Observations made by the author:

- "The design process as it is currently modeled in theory does not accurately match what happens in practice."
- "The engineering design process is still not completely understood."

Conclusions drawn from a quantitative analysis of the data include:

- "The activity which accounted for the highest proportion of the overall design effort was reviewing and reporting and the most used design-related technique was communicating by means of reviews and reports."
- "Over 50 percent of the observed project effort involved people working alone or in pairs on specified tasks; 30 percent went on meetings involving two, three, or four people; and 9 percent was spent on letter-writing (or reading) and telephone calls."

c. Retrospective Analysis

Johnson, Edgar M., "The Role of Man in the System Design Process: The Unresolved Dilemma," *System Design: Behavioral Perspectives on Designers, Tools, and*

Organizations (ed. by William B. Rouse and Kenneth R. Boff), New York: North-Holland, 1987, pp. 159-175.

ABSTRACT: "In the design and development of military systems, man is becoming recognized as a critical element that contributes significantly to system performance. A number of trends in the systems development and acquisition process have contributed to this view. The results of case studies are used to illustrate deficiencies in considering man as a design element and also to illustrate the complexity of the issue of integrating human requirements into systems design. The broad strategy to consider man as a design element is simple; the tactics are complex. Observations are made concerning some of the key elements influencing the shift to this emerging view of man's role in systems. Recommendations concerning the system development process and the field of human factors are made for translating what we know about human factors into action."

US Army Research Institute.

Little, S.E., "Incremental and Systemic Innovation Strategies: Reflections of Technical Choice," *Design Studies*, Vol. 8, No. 1, January 1987, pp. 41-54.

ABSTRACT: "This paper addresses the relationship between design strategies and the range of alternative technical solutions available to designers. The relationship between systemic and incremental change is examined in the light of examples taken from the aircraft industry and the modernization of Britain's railways. The use of the term 'systemic' rather than 'radical' is explained."

Computing and Information Studies, Griffith University, Australia.

Peterson, James G., Michael Hagel, Gerald Nadler, and Mark H. Chignell, "Aids to the Design Process Based on Techniques used by Expert Designers," *Preprints of the Proceedings of the 1988 NSF Grantee Workshop on Design Theory and Methodology*, Troy, New York, June 1988, pp. 1.3.1-1.3.10.

The focus of this project is the identification of process and decision aids in design. To do this, a structured interview procedure was developed to explore the features of design in a successful real-world design project. This technique was designed to combine the advantages of a "think aloud" method with a definitive set of broad-based and specific questions ranging from strategic issues in design to design team functions. Tentative conclusions reached include:

- There is little or no evidence of transportable or robust process aids acrcss engineering design domains.
- There is very little evidence of process aids in conceptual design where the global mission, purposes, and aims are transformed into functional specifications.

- The assertion that designers divide and conquer troublesome design problems, or decompose goals into subgoals, is not supported by the results of retrospective case histories.
- There is little evidence of design "reasoning" after the fact.
- There is insufficient evidence to reveal and characterize the "black box" in conceptual design.
- Given the timeline scenario methodology, it was very difficult to test hypotheses using retrospective case studies.

Petroski, H. "Design as Obviating Failure," *Proceedings of the 1987 International Congress on Planning and Design Theory*, ed. G. Nadler, Boston, MA, August 1987, pp. 49-53.

> ABSTRACT: "The systematic avoidance of failure is what characterizes rational design. Thus historical case studies of failures are full of important information for successful design, and the designer who is unfamiliar with the history of failures risks repeating old mistakes. Rather than being discussed merely in generalities in this paper, these ideas are explained in the context of the specific structural engineering example of bridges."
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> Department of Civil and Environmental Engineering, Duke University.

Promisel, D.M., C.R. Hartel, J.D. Kaplan, A. Marcus, and J.A. Whittenburg, "Reverse Engineering: Human Factors, Manpower, Personnel, and Training in the Weapon System Acquisition Process," *Technical Report 659*, Alexandria, VA, US Army Research Institute, January 1985.

> ABSTRACT: "The objective of the Reverse Engineering Project is to identify how and where to influence the acquisition process to result in effective use of soldiers in weapons systems. The project was initiated by the US Army Research Institute at the request of General Maxwell Thurman while he was Deputy Chief of Staff for Personnel. It was his position that careful examination of the development process of several Army weapon systems would provide specific illustrations of human factors, manpower, personnel, and training (HMPT) issues and identify critical events in the weapon system acquisition process (WSAP). If proper attention from an HMPT perspective were given to these critical events, then fielding of operationally useful systems would be facilitated. Approaches for accomplishing this would be developed based on the detailed information acquired from the study of the individual systems.
>
> "A study was undertaken based on the "reverse engineering" of four systems: STINGER, Multiple Launch Rocket System (MLRS), BLACK HAWK (UH-60A), and the Fault Detection and Isolation Subsystems of the M1 tank. The term "reverse engineering" is intended to suggest the process of determining how product of the WSAP came to be as they are. This is the final report of the project. It contains a description of the study process, brief summaries of the analysis of the individual systems, the synthesis of the four systems studies, and the recommendations and products that were developed."

Nutt, P.C., "Sources of Design Failure," *Proceedings of the 1987 International Congress on Planning and Design in Management of Business and Organization*, ed. P.C. Nutt, Boston, MA, August 1987, pp. 9-15.

ABSTRACT: "Case studies of design projects were analyzed to identify tactics associated with failure. These tactics are applied at three key points in the design process: when intentions are set, ideas are generated, and designs are implemented. A variety of tactics are used by designers at each of these points with some leading to higher rates of failure than others. Failure was associated with imposed ideas on the design process, adopting ideas after a limited search, and using power tactics to implement designs. Suggestions to improve design practice are offered."

Ohio State University.

Waldron, K.J. and M.B. Waldron, "A Retrospective Study of a Complex Mechanical System Design," *The Study of the Design Process: A Workshop* (Coordinated by M.B. Waldron), National Science Foundation Grant DMC 8614639, Oakland, CA, February 1987, pp. 99-128.

d. Expert System Knowledge Representation

Kurumatani, Koichi and Hiroyuki Yoshikawa, "Representation of Design Knowledge Based on General Design Theory," *Proceedings of the International Conference on Engineering Design*, August 1987, Boston, MA, pp. 723-730.

Describes a methodology for representing design knowledge (design objects and processes) in a computer by using an object-oriented approach. The authors are using this methodology to develop a "detail-design-aiding" system.

The University of Tokyo, Department of Precision Machinery Engineering.

Maher, Mary Lou, "Engineering Design Synthesis: A Domain Independent Representation," *Preprints of the Design Theory '88 NSF Grantee Workshop on Design Theory and Methodology*, Troy, NY, June 1988, pp. 3.4.1 - 3.4.16.

This research focuses on the development of a domain-independent knowledge-based system for preliminary design synthesis. The author describes design as a search process during which a design space is traversed for an acceptable solution. To implement a knowledge-based system which corresponds to this view of design, the design space (the knowledge used during design) must be well-represented. The knowledge that is used during synthesis is characterized in terms of planning knowledge (design goals, and the order in which goals are pursued) and design knowledge (alternative solutions for each goal, constraints on the selection of solutions). This knowledge is represented in frames: planning and design knowledge in hierarchically organized goal frames and the design solution in hierarchically organized component frames.

Gero, J., M.L. Maher, and F. Zhao, "Chunking Structural Design Knowledge as Prototypes," *Preprints of the Design Theory '88 NSF Grantee Workshop on Design Theory and Methodology*, Troy, NY, June 1988, pp. 4.2.1-4.2.18.

ABSTRACT: "The concept of a prototype as a conceptual schema for the representation of generalized design knowledge is proposed. A formal definition of prototypes is presented independent of their implementation. The paper elaborates this concept and demonstrates its applicability through an example in the domain of structural design. The example of prototype knowledge is presented for the design of rigid frames and the process of designing using prototypes is described. The advantages of this approach are presented."

McCall, R. "PHIBIS: Procedurally Hierarchical Issue-Based Information Systems."

This paper describes PHIBIS, a concept which extends the Issue-Based Information System (IBIS) method. PHIBIS is a design method for both describing design processes and attempting to improve them. The descriptive aspects of PHIBIS are based on the Issue-Serve Systems Theory. The Issue-Serve Systems Theory is a general theory which attempts to provide a theoretical framework for unifying specific partial theories such as theories of form, decision making, and participatory design. The Issue-Serve System Theory is stated as follows: "a design process can be represented as a quasi-hierarchy of issues connected by serve relationships, where (1) an issue is any question arising in a design project, (2) issue A serves issue B if answering A is useful for answering B, and (3) a quasi-hierarchy is a tree-like directed graph structure which contains a single top-most ("root") issue and mostly convergent branches and loops." Manual (noncomputer) implementation of PHIBIS was attempted in 1979 but proved to be infeasible. Computer implementation was begun in 1980 in a program called MICROcomputer Planning Information System (MICROPLIS).

University of Colorado at Boulder, College of Environmental Design.

Dixon, J.R., and M.K. Simmons, "Computers that Design: Expert Systems for Mechanical Engineers," *Computers in Mechanical Engineering*, Vol. 2, Issue 3, November 1983, pp. 10-18.

The authors introduce the notion of applying expert system technology to the field of mechanical engineering. An expert system is defined as a computer program that has "captured the experience, knowledge, and judgment of an expert practitioner in a field and has organized that expertise for use by other practitioners." The engineering design process is characterized as an ill-structured problem which involves iterative decision-making. Two types of decisions are described: technical decisions and process decisions.

Dixon, J.R.and M.K. Simmons, "An Architecture for Application of Artificial Intelligence to Design," in *Proceedings of the 21st Design Automation Conference*, 1984, pp. 634-640.

Describes the decisions designers make and fundamental characteristics of the design process and relates these decisions to the redesign model of the design process. The authors use the redesign model as the basis for an architecture for applying AI to design and illustrate the potential use of the architecture in two domains from mechanical engineering.

Dixon, J.R.and M.K. Simmons, "Reasoning About Quantitative Methods in Engineering Design," in *Coupling Symbolic and Numerical Computing in Expert Systems*, (ed. J.S. Kowalik), Elsevier Science Publishers, 1986, pp. 47-56.

Describes research which "addresses the expert behavior involved in the process of synthesizing a design for an engineered object." The research is based on the redesign model of the design process and focuses on what knowledge is used to refine a design to correct its faults (the redesign step). This involves addressing the "kinds of knowledge that must be captured in the qualitative description of a quantitative method...to provide an adequate understanding of these methods as regards their applicability and utility in a given situation." Initial findings suggest that the "knowledge required for the redesign step is primarily knowledge of the dependencies in the problem."

Dixon, John R., Adele Howe, Paul R. Cohen, and Melvin K. Simmons, "Dominic I: Progress Toward Domain Independence in Design by Iterative Redesign," *Proceedings of the ASME Computers in Engineering Conference*, Chicago, IL, July 20-24, 1986.

This paper describes a knowledge-based software implementation of a strategy for parametric design called iterative redesign. Design is modeled "as a process of repeated decomposition into subproblems until the subproblems are solvable as entities without further decomposition." Iterative redesign "is a model for design problem solving when the problem requires no further decomposition to be manageable intellectually. The software implementation of this strategy is called Dominic. The knowledge base consists of domain specific information including: problem specification parameters, design variables, performance parameters, priorities, satisfaction scales, analysis procedures, constraint equations, and constant values. Dominic has been successfully tested in four different design domains.

University of Massachusetts, Amherst, Department of Mechanical Engineering, Department of Computer and Information Science; General Electric Corporate Research and Development, Schenectady, NY.

Orelup, Mark F., John R. Dixon, and Melvin K. Simmons, "Dominic II: More Progress Towards Domain Independent Design by Iterative Redesign," *ASME WAM*, December 13, 1987, Boston, MA.

Meunier, Kenneth L. and John R. Dixon, "Iterative Respecification: a Computational Model for Hierarchical Mechanical System Design," Draft submitted to the 1988 ASME Computers in Engineering Conference.

The authors describe a hierarchical *computational model* for parametric mechanical system design called "iterative respecification." In this model, the design process is modeled as a hierarchical tree structure with the root and interior nodes representing subsystem managers, and the terminal nodes representing component designers. The manager nodes write problem specifications for component designs and resolve conflicts. The component designer nodes produce a component that meets the specifications. Computational models are defined as models that can be used as the basis for domain independent computer programs that perform design, but are not necessarily an emulation of how people do design.

Mitchell, Tom M., Louis I. Steinberg, and Jeffrey S. Shulman, "A Knowledge-Based Approach to Design," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. PAMI-7, No. 5, September 1985, pp. 502-510.

This research focuses on the development of an interactive knowledge-based consultant for VLSI design (called VEXED, VLSI expert editor). The VLSI design process consists of decisions regarding how to implement submodules. VEXED is a prototype of an implementation of a model of VLSI design which draws substantially from the model of design in the MOLGEN system. "VEXED's underlying model of design leaves the user with two types of decisions: which module to refine next, and which refinement rule to use." VEXED makes use of three categories of knowledge: knowledge of implementation methods for generating possible designs, control knowledge for guiding the search for satisfactory designs, and causal knowledge for propagating constraints among subparts of the designed artifact.

Rutgers University, Computer-Science Department.

Steinberg, L.I. and Tom Mitchell, "A Knowledge-based Approach to VLSI CAD, The Redesign System," *Proceedings of the 21st Design Automation Conference*, 1984, pp. 412-418.

This article describes experiences the authors had in developing REDESIGN, "a knowledge-based system for providing interactive aid in the functional redesign of digital circuits...REDESIGN addresses the following problem of functional redesign: Given an existing circuit, its functional specifications, and a desired change to these specifications, help the user to determine a change in the circuit that will allow it to meet the altered functional specifications without introducing undesirable side-effects." REDESIGN uses two separate models of reasoning to answer questions that arise when redesigning a circuit: causal reasoning and reasoning about purpose. "In reasoning about causality, REDESIGN describes both the behavior and the specifications for a data stream...In reasoning about purposes,...viewed the original design process essentially as a planning problem, with subgoals derived both from the decomposition of parent goals and from conflicts between other subgoals." Design expertise is represented in production rules.

Rutgers University, Department of Computer Science.

Steinberg, L.I. and T. Mitchell, "The Redesign System: A Knowledge-Based Approach to VLSI CAD," *IEEE Design and Test,* February 1985, pp. 45-54.

Mostow, Jack and Mike Barley, "Automated Reuse of Design Plans," *Proceedings of the International Conference on Engineering Design*, Boston, MA, August 1987, pp. 632-647.

The authors are working on the development of BOGART, a component of VEXED, which attempts to automate the reuse of *design processes* (i.e., the decisions made by the designer). The user decisions recorded by VEXED include "which module to refine next, and which refinement rule to use." Bogart provides the means for replaying suitable design plans.

Rutgers University, Computer Science Department.

Brown, David C. and B. Chandrasekaran, "An Approach to Expert Systems for Mechanical Design," in *Trends and Applications '83*, IEEE Computer Society, NBS, Gaithersburg, MD, May 1983, pp. 173-180.

This research is focused on the design of mechanical components by computer. Specifically, the authors are involved in a study of "design activity in order to be able to characterize exactly what kind of design tasks can be handled using AI techniques." The research has been limited to "that class of design activity which is the most routine, where a designer follows a set of well-established design alternatives at each stage of the design." The approach under development in this study involves the "refinement of a design by a hierarchy of conceptual specialists that solve the problem in a distributed manner, top-down, choosing from sets of plans and refining the design at each level of the hierarchy." Each specialist has different expertise. Plans consist of a "collection of tasks or calls to specialists, possibly interspersed with constraints. Each task is a coherent collection of steps, where a step makes a single design decision. This approach is called Design Refinement."

In this research, design is modeled as a process consisting of a number of points at which alternative possible sequences of actions may be pursued. "At each point, the choice may be simple, but the accumulated effect is that of quite complex problem solving behavior."

An ultimate goal of this research is to understand what kind of knowledge structures and problem-solving strategies might be needed for more general design.

Ohio State University, Department of Computer and Information Science.

Brown, D.C. and B. Chandrasekaran, "An Expert System for Mechanical Design: A Progress Report."

This is an extended abstract which describes progress on the implementation of a prototype expert system for air cylinder design using the Design Refinement approach.

Brown, D.C., "Capturing Mechanical Design Knowledge," 1985, pp. 121-129.

This article describes a language called Design Specialists and Plans Language (DSPL), developed in concurrence with research on the design refinement approach. It was "developed in order to implement the AIR-CYL system. It provides a way of writing declarations of Specialists, Plans, Tasks, Steps, Constraints, Failure Handlers, Redesigners, Sponsors, and Selectors, allowing the user to specify the knowledge contained in them."

Worcester Polytechnic Institute, Computer Science Department.

Brown, David C. and B. Chandrasekaran, "Knowledge and Control for a Mechanical Design Expert System," *IEEE Expert*, 1986.

Makes the assertion "a large unstructured collection of rules clearly lacks validity as a realistic model of design because reducing all knowledge to a single form does not recognize that there are many different types of knowledge used in any design problem-solving activity."

Kalay, Y.E., L.M. Swerdloff, and A.C. Harfmann, "A Knowledge-based Approach to Dynamic Computer-Aided Design Task Allocation," *Proceedings of the Conference on Planning and Design in Architecture*, Vol. I00239, Boston, MA, August 1987.

This research focuses on the development of fundamental paradigms of design as a computable process. The basis of the research is Simon's state-transition model of problem-solving where states represent solutions and transitions represent processes that produce new candidates for consideration as potential solutions. This model has been modified slightly in that states represent design goals. Transitions are defined in terms of processes that map out design planning strategies among the alternative goals. Goals represent design knowledge by which candidate design solutions are evaluated. Thus the design process is represented in terms of milestones. This paradigm has been tested through a PROLOG implementation.

State University of New York at Buffalo, School of Architecture and Environmental Design.

Velinsky, S.A. and M.F. Lembeck, "Progress Towards an Expert System Environment for Design," *The Study of the Design Process: A Workshop* (Coordinated by M.B. Waldron), National Science Foundation Grant DMC 8614639, Oakland, CA, February 1987, pp. 533-548.

The focus of this research is on the development of an expert system that interacts with analysis packages for design development purposes. The system is being applied to the design of wire rope based mechanical systems and is referred to as Mechanically Intelligent Designer (MIND). MIND embodies a basic five-step model of the design process. Top-level control of the design process is carried out by a special ruleset. Each sub-task has a corresponding rule-set. When a rule's consequent requires an analysis

package, the inference engine calls that package. The authors have found that:

- The realm of design problems is so vast and each problem is so specific that an all encompassing inference engine is considerably difficult to develop. Thus, rather than having general rules about design, our system uses domain specific design rules obtained from an expert.
- Engineering design is often highly analysis-based and, thus, an expert design system must be able to interact with analysis packages.
- Hardware limitations can prevent an expert design system from paralleling the best human designer's approach, i.e., many computers have a single processor, whereas the human designers approach can be viewed as multi-processor based. However, this does not prohibit the system from designing, but merely guides the form of the expert system's design methodology. The expert system does not have to mimic the human exactly to arrive at similar, if not better, results."

University of Wisconsin-Madison, Department of Mechanical Engineering.

Rychener, Michael D., "Expert Systems for Engineering Design," *Expert Systems,* Vol. 2, No. 1, January 1985, pp. 30-44.

Provides a good overview of expert system technology in general and with respect to engineering design problems. Briefly describes a few prototypical AI systems that embody techniques that can be applied to engineering design problems. An annotated bibliography is included.

Ulrich, Karl and Warren Seering, "A Computational Approach to Conceptual Design," *Proceedings of the International Conference on Engineering Design*, Boston, MA, August 1987, pp. 689-696.

This study focuses on the conceptual phase of mechanical design to "better understand how new ideas for mechanical devices can be generated." The key hypothesis of this study is that "most new designs come from knowledge of old designs." To test this hypothesis the authors are developing "well-defined procedures which operate on a well-defined representation of a particular domain of objects and representations." As a starting point, the authors are studying novel combination, "the process of extracting individual structural attributes from each of several known devices and combining these attributes in novel ways to create structural description of new devices."

Design knowledge used for novel combination can be represented computationally as a "network of functional and structural attributes linked by causal relations." With this knowledge representation scheme, the authors "have implemented a program which does novel combination in the domain of mechanical fasteners." The authors found that the successful application of the novel combination procedures depends on a fixed framework for the form of the solution (the structural and functional attributes of the design solution can be completely identified and structured prior to the realization of the solution). When there is a fixed framework,

design knowledge and solutions can be readily described. The solution to most design problems, however, cannot now be described a priori within a fixed framework. Thus the applicability of novel combination is limited in the domain of engineering design.

MIT, AI Laboratory.

Ward, A. and Waren Seering, "An Approach to Computational Aids for Mechanical Design," *Proceedings of the International Conference on Engineering Design*, Boston, MA, August 1987, pp. 591-597.

The goal of this research is to "develop programming methodologies adequate for performing routine design tasks" on complex mechanical systems. The approach taken is to write object modules, each representing a type of design component. Each object contains parameters describing the component, implements specific engineering equations and methods to calculate further parameter values, and exchanges information with other objects as appropriate. Design decisions are made by passing messages among the objects. Results from the research suggest that program objects can be used to represent components of a design; writing the objects, however, is a difficult task.

Wood, Kristin L. and Erik K. Antonsson, "Engineering Design - Computational Tools in the SYNTHESIS Domain," *The Study of the Design Process: A Workshop* (Coordinated by M.B. Waldron), National Science Foundation Grant DMC 8614639, Oakland, CA, February 1987, pp. 75-95.

The focus of this research is on the development of computational tools for the preliminary phase of design. The research emphasizes the synthesis and decision components of engineering design. In this paper, the authors present a model of the engineering design process with respect to the actions of the engineer in the process of design (not necessarily the thoughts he has while designing). This model is based on a decision structure in the form of a hierarchical tree. The root of the tree is the need. The branches are the overall design choices. This model serves as a foundation, but does not help the engineer in everyday practice. To build upon the foundation, a systematic approach to design based on the Becker model (fuzzy set theory) is constructed. The authors' results in a symbolic and graphical representation of the design process following a data-flow paradigm.

California Institute of Technology, Department of Mechanical Engineering.

2. Methods Used to Model the Individual Design Decision Process

a. Protocol Analysis

Ballay, Joseph M, "An Experimental View of the Design Process," in *System Design, Behavioral Perspective on Designers, Tools, and Organizations*, ed. William B. Rouse and Kenneth R. Boff, New York: North Holland, pp. 65-82.

This paper describes "patterns of problem solving revealed by experiments with designers using traditional methods and computer-aided systems to solve a typical industrial design problem." The goal of the research was to understand how the design process was affected by the use of CAD systems. During this study, the authors observed 50 designers, design students, engineers, and draftsmen, completed a detailed protocol analysis with 18 subjects, and observed one subject over 20 hours of design activity. The results from the analysis of the amassed data suggest basic patterns for three kinds of activity in the overall design process: planning, routine primary processes, and workplace management. A couple of observations about these patterns:

- "The more kinds of representation a designer can use, the better able he is to work through complex problems.
- The role and function of the computer changes as the design process progresses. At the beginning, it is a tool for individual problem solving...Toward the end, it becomes a tool for group management or communication."

Center for Art and Technology, Carnegie-Mellon University.

Eckersley, Michael. "The Form of Design Processes: A Protocol Analysis Study." *Design Studies*, Vol. 9, No. 2, April 1988, pp. 86-94.

The goal of this research is to use protocol analysis as a method to analyze the verbal behavior of designers involved in problem-solving. Primary hypothesis tested: "designers vary significantly in the nature and amount of information processed during problem-solving." Secondary, informal hypothesis: stages in problem solving become evident in the analysis of protocol data. Problem domain: interior design.

Significance of the study: "The first of its kind to:

- Chart design problem-solving behavior over time across eight variables
- Utilize specially developed computer programs to streamline the encoding and analysis of verbal protocols
- Use a sample of three encoders to construct a more veridical interpretation of protocols
- Allow for a modest testing of experimental hypotheses."

The author defines protocol analysis as "a research methodology based on the psychological theory of information processing. Protocol analysis offers the community of design scientists a potentially effective method for the controlled observation and experimental analysis of design problem-solving behavior."

The author reviews related literature. According to this review: Akin conducted the first PA study recorded in the design literature. (1984)

Design decision process model: The authors attempted to model problem-solving behavior as patterns in the occurrences of different types of verbalizations (literal copy statements, paraphrased statements, inferences, intentions/plans, move, search, specific assessment, general assessment, and none of the above) during the design process. These verbalization categories correspond to the types of information processed during problem-solving. An analysis of the protocols revealed no general patterns across all subjects. The authors concluded that the lack of verbalization patterns suggests that "designers vary significantly in the nature and amount of information processed during problem solving."

Conclusion: "Much work remains to be done in order to establish Protocol Analysis as a valid design research tool. The potential for experimentally testing research hypotheses is great, provided larger subject-samples are utilized..."

Results:

- Study was successful in testing the methodology
- Working hypotheses were confirmed.

University of Maryland, Department of Design.

Malhotra, Ashok, John C. Thomas, John M. Carroll, and Lance A. Miller, *Cognitive Processes in Design*, IBM Thomas J. Watson Research Center, Report RC-7082, 1978.

This study was conducted for the Office of Naval Research by the Behavioral Sciences Group at the IBM T.J. Watson Research Center. Focus of the research: identify and characterize important design processes: goal elaboration, design generation, and design evaluation. Goal: Attain an understanding of the kinds of aids that can assist the design process and make it more efficient and more effective. Research methodology: one observational study and two empirical studies of the design process.

Model developed:

- Explicitly allows iteration and recursion
- Provides criteria for identifying phases of design
- Provides a framework within which specific hypotheses can be empirically tested.

Problem-solving paradigm underlying research: "A problem state is said to exist when a human has a goal but no immediate procedure that will guarantee attainment of the goal. The goal may be a satisfaction to be achieved or a dissatisfaction to be alleviated. Problem-solving occurs in moving from a problem state to a non-problem state. In problem-solving, then, a person begins in an initial state, uses transformations that move him from one state to another, and ends in a final state. Any of these states and transformations may be well-defined or ill-defined.

In the case of design problems, the person is generally not forced to start from a specific initial state, and although there may be constraints on what may be used, the transformations are usually not limited. In real-world design situations the goals are, typically, fuzzy and poorly articulated and cannot be mapped directly into properties of the design. Thus, the exact configuration of the final state is not prescribed. A part of the design process consists of formalizing and refining the design goals into functional requirements that can be matched by properties of the design."

Observational study method: Study "consisted of video-taping actual problem-oriented dialogs between real people, playing real roles, and attempting to solve real-world problems. The analyses are based on transcriptions of the videotapes....Scenario: a client (C) confronts a consultant, expert, or designer (D) with a problem and the expert is expected to provide a solution to this problem....Actual C-D dialogs include the examination of (partial) proposed designs to test if they violate some unstated goal, the domination of a design solution by a better one, and the consolidation of design components into a final design."

Observed behavior: "C-D dialogs consisted of a series of 'cycles'; each cycle consisting of a regular succession of 'states.' A state is defined as a portion of the dialog that is oriented towards a single purpose....C-D dialogs are structured into cycles each of which consists of introducing some requirements, discussing them, outlining a solution, and elaborating and exploring it. The solutions proposed in a cycle do not, however, always match the requirements discussed in it. Unsatisfied requirements are carried implicitly into subsequent cycles."

Model of the design process: The design process is decomposed into three fundamental underlying processes: goal elaboration, design generation, and design evaluation.

Implications and conclusions: The proposed model suggests the characteristics of aids to the various sub-processes within the design process:

- *Aids to Goal Elaboration*: "One strategy for assisting the goal elaboration process is suggested by the C-D dialogs: Provide a mechanism for describing a number of designs that may or may not be appropriate to the client.
- *Aids to design generation*: "Should assist the designer in generating design elements and design organizations to meet specified functional requirements...in many cases...the purpose of the aid should be to help him retrieve the information...in other cases, the designer may have to search for design elements and organizations in the outside world."
- *Aids to design evaluation*: "The designs must be represented in a formal manner and the properties of the design derived mathematically from the design specifications."

Stauffer, L.A., D.G. Ullman, and T.G. Dietterich, "Protocol Analysis of Mechanical Engineering Design," *Proceedings of the International Conference on Engineering Design,* August 1987, Boston, MA, pp. 123-137.

Stauffer, L.A., David G. Ullman, and Thomas G. Dietterich, "Preliminary Results of an Experimental Study of the Mechanical Design Process," in *The Study of the Design Process: A Workshop* (Coordinated by M.B. Waldron), Oakland, CA, February 1987, pp. 157-199.

Ullman, David G., Stephen Wood, and David Craig, "The Importance of Drawing in the Mechanical Design Process," *Design Process Research Group*, DPRG-89-1, Department of Mechanical Engineering, Oregon State University, Corvallis, OR, January 1989.

> This paper is a study on the importance of drawing (both formal drafting and informal sketching) in the process of mechanical design. Five hypotheses, focused on the types of drawings, their necessity in mechanical problem solving, and their relation to the external representation medium are presented and supported. Support is through referenced studies in other domains and the results of protocol studies performed on four mechanical designers. Video tapes of all the marks-on-paper made by designers in representative sections of the design process were studied in detail for their type and purpose. The resulting data is supportive of the hypothesis. These results also give requirements for future computer-aided design tools and graphics education and goals for further studies.

Ullman, D.G., T.G. Dietterich, and L.A. Stauffer, "A Model of the Mechanical Design Process Based on Empirical Data," *AI-EDAM*, Vol. 2, No. 1, 1988, pp. 33-52..

> Describes the results from a two-year study of the mechanical design process based on the evaluation of experienced mechanical designers solving real design problems.
>
> *Research Method*: Five mechanical design engineers were given initial specifications for one of two simple industrial design problems. "Their verbal reports, sketches, and gestures were video-taped and audio-taped for a period of 6-10 hours..."
>
> *Results*: An ongoing analysis of the data has lead to the development of a model of the design process called TEAM (task-episode accumulation model). TEAM "explains many aspects of the design process and it provides significant insight into the way designs are developed."
>
> "TEAM is a problem-space model in which the fundamental components are the design state and the design operators. The design state contains all information about the evolving design including problem specifications, additional constraints introduced by the designer, proposed designs, drawings, calculations, assembly plans, and so on. Design operators are primitive information processes that modify the design state by performing calculations, creating new proposed designs, evaluating proposed designs, and making decisions to accept or reject proposed designs. TEAM contains

10 operators: select, create, simulate, calculate, compare, accept, reject, suspend, patch, and refine."

"To accomplish a design, the design engineer applies the primitive operators in meaningful sequences called episodes. An episode is a sequence of operator applications that address some primitive goal...Within an episode, the decisions about what operator to apply next is guided by a set of heuristic rules."

"According to TEAM, the goal structure of the design process has three main levels. At the highest level is the main goal comprising the satisfaction of the given constraints. This top-level goal is decomposed into finer goals, each of which is solved by a single task. These task-level goals are further decomposed into the primitive goals that are each addressed by an episode."

Significance of model: This overall problem-solving strategy selects, at each episode, the alternative that seems best. "There is no global search that constructs whole alternative proposals in detail and evaluates them to select the best. Our designer subjects are satisficers, not optimizers."

For this strategy to succeed:

(1) Designers must choose a good conceptual design during the early episodes,

(2) Designers must be able to generate and select good refinements throughout the design, and

(3) Designers must be able to identify constraint violations and apply good patches to the design.

This work is based on models of information processing psychology developed by Newell and Simon.

Conclusions: "The development...of TEAM...has shown the usefulness of protocol analysis as an exploratory tool for studying the design process. There is still more protocol analysis can tell us about the design process, especially in the area of identifying the ways designers represent and reason about proposals and constraints."

Ullman, D.G.and T.G. Dietterich, "Progress in Understanding the Process of Mechanical Design," *Design Theory 1988 NSF Grantee Workshop on Design Theory and Methodology*, Rensselaer Polytechnic Institute, June 3-5, 1988, pp. 1.1.1- 1.1.11.

Discusses results of the NSF-sponsored study described above. The objectives of this study were to

- Develop a model of the design process from empirical data,
- Develop representations for mechanical design data, and
- Design software to test the findings.

The mechanical design process and the results from this study will be examined in greater detail during a new three-year study. One specific goal of the new study is "to design and implement a design history tool."

Ullman, David G. (Department of Mechanical Engineering), Thomas G. Dietterich (Department of Computer Science), "Research Overview," *Mechanical Design Process Research Group*, Oregon State University, Corvallis OR, November 1988.

The Mechanical Design Process Research Group is a four-year old association of faculty and students at Oregon State University. Members of this group have a common interest in the study of the mechanical design process and the potential for applying computer techniques to improve design performance. The group, led by Associate Professors David Ullman and Thomas Dietterich, has had the involvement of other faculty in Mechanical Engineering and Computer Science, along with faculty in Industrial Engineering and Psychology. Most notable of these has been the contribution of Professor Donna Cruse of the Psychology Department.

To date, 15 graduate and 5 undergraduate students have taken part in the research effort, with one granted PhD (now an Assistant Professor at the University of Idaho) and six completed masters degrees. The status of many current students in the group are presented in the discussion of the current research efforts. This is preceded by the Group's goals and accomplishments.

Ullman, David G., "A Taxonomy of Mechanical Design," *Department of Mechanical Engineering*, Oregon State University, Corvallis, OR, 23 December 1988.

In this paper, a taxonomy for mechanical design has been developed and used to compare and contrast differing research and mechanical design tool developments. It has the potential of forming a basis for classification for all mechanical design research. Specifically, if all proposals for research on the mechanical design process had to have a section where the effort was classified according to a taxonomy such as that proposed here, then evaluating the proposals may be made much easier. At least reviewers would have an initial guide on how to view the research. If the proposers found that the taxonomy was too constrictive to allow for adequate classification, then they could state why and propose a change to the taxonomy. Research reports on mechanical design process could also classify themselves accordingly.

Additionally, the taxonomy may be useful in accrediting academic programs. Within academia, the term "design" has always been ambiguous. As part of an accredited undergraduate curriculum, there must be a significant portion of design in the curriculum. However, this has been hard to measure, much less enforce. It is, however, possible to define a clearer and more measurable definition of design using the taxonomy. For example: Courses that rely solely on parametric techniques (in terms of transforming from artifact types to specific instances), such as mechanical component design and most fluid-thermal design courses, could be considered Category 1 courses. Courses that develop perceived need to concepts could be Category 2 courses. The accreditation requirement could be for credit in both Category 1 and Category 2 courses. The gradation could be made even finer if desired.

It must be reiterated that this taxonomy is seen as a first step. It is hoped that the community adopts it and refines it as the discipline of mechanical design becomes better defined and more of a formal science.

b. Laboratory and Computational Experiments of Problem Solving Behavior

Dyer, Michael, G. and Margot Flowers, "Automating Design Invention," *Autofact 6 Conference Proceedings*, October 1-4, 1984, Anaheim, CA, pp. 25.1-25.21.

The authors are "interested in understanding all of those cognitive skills which engineers possess," and are addressing the application of AI research to design. The specific focus of the research is formalizing rules of creativity in the area of mechanical engineering design. In this paper, the authors show how rules of invention may be used in mechanical design. This research is implemented in an "intelligent design invention system (IDIS).

University of California at Los Angeles.

Design Process Model: "The process of invention...is viewed as a search through a large space of states representing objects or ideas. Movement from one state to another is accomplished by the application of an operator. In our case, the state space consists of object designs and the operators are "creativity rules" or rule schemas which modify or combine existing objects to yield new designs."

Findler, Nicholas, V., "Analogical Reasoning in Design Processes," *Design Studies*, Vol. 2, No. 1, January 1981, pp. 45-51.

This research is based on the contention that design is an "ill-structured" problem and thus is difficult to solve by any set algorithm. Preliminary studies focus on the role of analogical reasoning in design problem solving by computers. Specifically addresses the problem of what information should be extracted from raw experience consisting of descriptions of problems and solutions, and how this information can then be used in determining solutions to new problems. This paper describes how certain programmable procedures (whose cognitive strategies are based on two different models of analogical reasoning) can transform raw experience in design problem solving into the knowledge base of an intelligent system.

The State University of New York at Buffalo, Department of Computer Science.

Fischer, Gerhard and Boecker Heinz-Dieter, "The Nature of Design Processes and How Computers Can Support Them," *European Conference on Integrated Interactive Computing Systems*, Stresa, Italy, September 1982.

> The authors are conducting research to improve man-machine communication through the creation of computer systems for cooperative problem-solving between man and machine. The particular focus is on systems which support design processes in different domains. Necessary preconditions for the design of these systems requires an understanding of: (1) the boundaries between domain-specific and domain independent design knowledge; (2) what a designer does; and (3) what type of difficulties a designer encounters. The research concepts are being implemented in a knowledge-based system called Information Manipulation System (INFORM). INFORM "incorporates the idea of a symbiotic environment of man and machine which combines the advantages of both to cooperatively solve design tasks which neither of them could solve as quickly and as easily alone." The knowledge base uses an object-oriented representation language.
>
> University of Stuttgart, Computer Science Department.

Frey, Claire E., Gerald Nadler, and Joseph M. Smith, "Problem Formulation Methods in Engineering Design," *The Study of the Design Process: A Workshop* (Coordinated by M.B. Waldron), Oakland, CA, February 1987, pp. 203-232.

> ABSTRACT: "This proposal hypothesizes that engineers can significantly improve their individual performances by adopting explicit methods found to be effective in taking a problem-as-stated and converting it into the 'right' problem on which to work. The specific objectives of this research are to:
>
> (1) Identify the techniques and tools used by successful engineers in developing a statement of the problem on which to work,
>
> (2) Experimentally evaluate various techniques for arriving at an effective problem statement,
>
> (3) Provide prescriptive guides (and computer aids) for the problem formulation phase of design which can be adopted by practicing engineers, and
>
> (4) Make available computer-recorded real-world problems and information which may be useful for student engineering education and perhaps eventually for professional engineering examinations."

Green, Douglas S.and David C. Brown, "Spatial Reasoning During Design: Fit and Assembly," *Proceedings of the International Conference on Engineering Design,* August 1987, Boston, MA, pp. 723-730.

> Research is directed towards understanding the knowledge used and problem-solving behavior exhibited during routine design tasks. Specifically addresses the question of how a designer determines the content of a constraint with respect to how well previously designed sub-components fit together. This spatial reasoning process is characterized as a

qualitative, sequential, four-stage process. Each stage represents a different set of decisions that must be made about the fit. The authors have implemented two stages of this model of spatial reasoning and have applied it to a simple example. Extensions are required to apply the model to more complex and realistic objects. Ultimate goal: understanding how design knowledge is compiled. This work is an outgrowth of the Brown and Chandrasekaran research on routine design.

Artificial Intelligence Research Group, Department of Computer Science, Worcester Polytechnic Institute.

Gross, Mark and Aaron Fleisher, "Design as the Exploration of Constraints," *Design Studies*, Vol 5, No. 3, July 1984, pp. 137-138.

The authors provide philosophical insights into knowledge-based systems for design and briefly describe work on a computer program which embodies the notion of "design as a society of experts." The motivation for the research is described by the authors:

> "We want to learn how to think about design--as architects do it. We have an idea or two. We propose to make of them a computer program. If the computer then acts a bit like an architect, then the experiment will have succeeded. We shall be pleased. Our theory survived; the program is worth a round of elaboration.
>
> The program is at once a theory and an experiment. As an experiment, it has the advantages of clarity and control. As a theory, it is disadvantaged by distance. All blessings are mixed."

The authors describe the difference between the early diagnostics-oriented expert systems which reason with data and facts and design programs: "The design program proceeds from preference, modulated by context and circumstance. It is headed by constraints."

The process of design is described as "an exploration of fixes that meet the constraints."

Massachusetts Institute of Technology.

Habraken, John N., "Concept Design Games," *The Study of the Design Process: A Workshop* (coordinated by M.B. Waldron), Oakland, CA, February 1987, pp. 133-154.

Hight, T.K., L. Ginszauskas, and D. MacLean, "Investigation into the Methods Students Use to Solve Mechanical Design Problems," *Proceedings of the International Conference on Engineering Design*, August 1987, Boston, MA, pp. 888-897.

ABSTRACT: "Two design exercises have been given to three undergraduate engineering classes to investigate students' approach to solving design problems. Upperclassmen were more organized and

thorough in response to an unstructured problem, and displayed a better understanding of the problem and a more complete view of the design process during a structured exercise."

Department of Mechanical Engineering, Santa Clara University.

Kerley, James, J., "Retroduction: A New Structured Approach to Mechanical Design," *Proceedings of the International Conference on Engineering Design,* August 1987, Boston, MA, pp. 123-137.

Pask, Gordon, *The Influence of Learning Strategy and Performance Strategy upon Engineering Design*, System Research LTD, Surrey, England, Progress Reports 3-7, 1976-1977.

These progress reports describe a study performed for AFOSR by System Research, Ltd., to evaluate the influence of cognitive style upon design ability in the domain of electronic engineering design. The main hypotheses under test in this study are:

Designers who exhibit high versatility scores on the stylistic tests will produce better rated designs. Versatility is a reliable index of potential design creativity.

The process of design will reveal a greater use of valid analogical reasoning on the part of designers deemed "good" on any of these criteria.

The research methodology is described as follows:

Designers from two groups (experienced designers and students) are pre-tested for learning style and scored in terms of operation learning, comprehension learning, and versatility. All subjects engage in a many session design task. The resulting designs are evaluated. Behavior during the design task is recorded conventionally (sketches, comments, etc.) and through a computerized interrogation program with which the designer records justifications and quantifiable explanations for his design. After completing individual assignments, the subjects are assembled into groups for a group design task. The object of the group sessions is to sample communication between designer, their activity as a team, and the influence of personal style and design performance upon their interaction. Dialog during group design is tape-recorded and content analyzed.

Preliminary results from the individual design sessions suggest that analogical reasoning is ubiquitous. The use...of analogy is frequent and, in contrast to exponents of an algorithmic model of design, a prominent part of both student and expert behavior.

Waldron, M.B., W. Jelinek, D. Owen, and K.J. Waldron, "A Study of Visual Recall Differences Between Expert and Naive Mechanical Designers," *Proceedings of the International Conference on Engineering Design,* August 1987, Boston, MA, pp. 86-93.

The purpose of this research is to develop a deeper understanding of the conceptual design process to design computer aids for conceptual design. This study, in particular, focuses on visual and spatial reasoning skills used by mechanical engineers during design conceptualization. The hypothesis under test was that as experience in ME design increases, the efficiency with which the designer copes with information should also increase. The experiment consisted of presenting ME drawings to three groups of subjects. Each subject was asked to look at each drawing and to reproduce it from memory on a sheet of paper. The total number of references to the drawing and the average time between references were recorded. Each subject was asked to think aloud while completing the task. Task performance protocols were also recorded for each use.

The authors conclude that the results of the study "support the original hypothesis that the efficiency of information handling by the mechanical designers is dependent on their level of expertise....Further, higher order information is dealt with at a higher symbolic level by the experts than by the naive designers. The naive seem to focus more on lines and sizes whereas experts focus on the features resulting in fewer errors, references, and longer drawing time between references."

C. OTHER SOURCES OF INTEREST

1. Design Theory

Alexander, E.R., "Design in Planning and Decision Making: Theory and Its Implications for Practice."

ABSTRACT: "Definitions of design are reviewed, and three models of the design process are presented. One definition sees the design as roughly equivalent to problem-solving or decision making, but in the context of the design professions. The alternative, "generic" definition sees design as the development of alternative courses of action. Three models of the design process are: I. Design as systematic search and information processing; II. Design as intuitive creativity; III. An integrative process combining Models I and II. The intrinsic contradictions between Models I and II are discussed. These imply the inadequacy of Model III and demand a more genuine synthesis. Directions for developing such a synthesis are suggested, and the adoption of the generic definition of design is advocated. Implications for design education are a mixed curriculum including both systematic and experiential teaching formats. Implications for practice are the lack of short-term answers, but the promise of an ultimately useful model of the design process."

Chandrasekaran, B., "Design: An Information Processing-Level Analysis," Draft Version of Chapter 2 of *Design Problem Solving: Knowledge Structures and Control Strategies*, Ohio State University Technical Report, January 1988.

ABSTRACT: "Design problem solving is analyzed as an information-processing task: the task and its information requirements are analyzed.

This analysis suggests possible decompositions of the task into a number of subtasks, depending upon what kinds of knowledge are in fact available in a domain. This decomposition can be carried on several levels until we reach an understanding of how various generic problem-solving capabilities can come together to help solve the design problem. This analysis suggests possible problem solving architectures for design. A number of AI approaches to design are discussed in this perspective and it is shown how each of them can be understood as solving a particular version of the design problem, using one of the architectures that arises from the analysis in such a way that the architecture matches the knowledge available in the domain."

Christakis, Alexander N., David B. Keever, and John N. Warfield, "Development of Generalized Design Theory and Methodology," in *The Study of the Design Process: A Workshop* (Coordinated by M.B. Waldron), Oakland, CA, February 1987, pp. 3-72.

Gasparski, W.W., "Design Skills: How to Find Them?," May 1980.

ABSTRACT: "After considering, from a methodological point of view, an 'ideal' procedure of design, a concrete application is proposed in the identification of design skills. Three types of design skill, associated with reception, transformation, and communication of design information, are analyzed in the form of a 'skills tree.' The paper ends with remarks on the importance of design education and on the guidelines for designing a design course."

Department of Praxiology, Polish Academy of Sciences, Warsaw.

Gregory, S.A., "Expert Systems Versus Creativity in Design," *Proceedings of the International Conference on Engineering Design,* August 1987, Boston, MA, pp. 615-621.

Provides a historical perspective of the study of the role of creativity in design with a particular emphasis on the contributions of expert system technology. The author raises some important questions regarding the development of suitable models of design that can be incorporated into expert systems.

Lindhult, M.S., "Towards an Intuitive Computer-Aided Design Process," *Proceedings of the Conference on Planning and Design in Architecture*, Vol. I00239, Boston, MA, August 1987.

Describes improvements needed to make CAD systems "more responsive to designers so that the computer will fit intuitively into the design process." This includes a summary of the major issues concerning the integration of expert systems with CAD.

University of Massachusetts, Amherst, Department of Landscape Architecture and Regional Planning.

Mostow, J., "Toward Better Models of the Design Process," *The AI Magazine*, Spring 1985, pp. 44-57.

ABSTRACT: "What are the powerful new ideas in knowledge based design? What important research issues require further investigation? Perhaps the key research problem in AI-based design for the 1980s is to develop better models of the design process. A comprehensive model of design should address the following aspects of the design process:

- The state of the design
- The goal structure of the design process
- Design decisions
- Rationales for design decisions
- Control of the design process
- The role of learning in design.

This article presents some of the most important ideas emerging from current AI research on design, especially ideas for better models of design. It is organized into sections dealing with each of the aspects of design listed above."

Nadler, Gerald, "Systems Methodology and Design," *Transactions on Systems, Man, and Cybernetics*, Vol. SMC-15, No. 6, December 1985, pp. 685-697.

ABSTRACT: The problems facing the economy and its productivity level and rate of change have many sources. One is related to engineering problem solving and design. Traditional and modern ways of handling engineering design problems are compared, and key issues that systems methodology and design (SMD) should address are developed. A review of several traditional sciences and disciplines (e.g., psychology, mathematics, philosophy) shows that SMD can be enhanced and extended to help improve the results obtained. A merger of different disciplines and pragmatic action-oriented perspectives of real-world concerns leads to the benefits of SMD: increase the probability of working on the right problem, provide a holistic view, identify the iterative process of design, treat each problem and recommendation as unique, improve significantly the likelihood of implementation, and define a solution as a flexible continually changing set of system specifications. Recommendations for increasing engineering success with SMD include changing design education for undergraduates to an SMD basis, relating management and engineering concepts, supporting increased funding for research, and getting the engineering societies to promote SMD while maintaining an active scholarly and research perspective so that SMD itself continually improves.

Ostrofsky, Benjamin, *Morphology of Design of Aerospace Systems with Inclusion of Human Factors*, Final Report under AFOSR Grant No. 77-3148, University of Houston, August 1977, AD A049999.

Pugh, Stuart, "Design Activity Models: Worldwide Emergence and Convergence," *Design Studies*, Vol. 7, No. 3, July 1986, pp. 167-173.

VDI 2221, *Systematic Approach to the Design of Technical Systems and Products Design Handbook*, VDI Society for Product Development, Design and Marketing, Committee for Systematic Design, translation of German Edition, November 1986.

2. Miscellaneous

Bots, P.W.G. and H.G. Sol, "An Environment to Support Problem Solving," *Decision Support Systems*, Vol. 3, No. 3, September 1987, pp. 225-231

The design process as a decision structure.

Chandrasekaran, B., "Towards a Taxonomy of Problem Solving Types," *AI Magazine*, Vol. 4, No. 1, Winter 1983, pp. 9-17.

Ericsson, K.A., Simon, Herbert A., *Protocol Analysis, Verbal Reports As Data*, The MIT Press, Massachusetts, 1984.

Kranzberg, M., "The Changing Ecology of Innovation," *Proceedings of the 1987 International Congress on Planning and Design Theory*, Edited by G. Nadler, Boston, MA, August 1987, pp. 41-47.

ABSTRACT: "Innovation is a process involving the coupling of creativity and vision with social needs, resource availability, economic constraints and opportunities--and occurring in a social cultural environment which is affected by political policies, military requirements, and a host of other factors. All these elements interact with one another, and they represent the social ecology of innovation. This dynamic interplay among the many elements comprising the environment of innovation has changed throughout history, and it is changing today. Because the author is a historian, he views the innovation process in historical terms, in order to provide some perspective on the nature and dynamism of this ecological process in today's world."

Meister, David, "A Cognitive Theory of Design and Requirements for a Behavioral Design Aid," *System Design: Behavioral Perspectives on Designers, Tools, and Organizations*, ed. by W.B. Rouse and K.R. Boff, New York: North Holland, 1987, pp. 229-244.

ABSTRACT: "The development of a support system to aid engineers in the solution of design problems (those with behavioral implications) has two prerequisites: The first is the construction of a meaningful theory of the engineer's cognitive processes in design; the second is the availability of empirical human performance data associated with design variables. The following paper outlines the beginnings of such a theory and describes the characteristics a design support system should have."

Nutt, P.C., "Paradigms for Doing Process Research," *Proceedings of the 1987 International Congress on Planning and Design Theory*, ed. G. Nadler, Boston, MA, August 1987, pp. 61-67.

ABSTRACT: "Design research has been largely devoted to exploring structure (the design), overlooking process. Process questions include what produced a design, how to use a design, and how to evolve or transform a design to meet new circumstances and conditions. The study of design should consider the structure-process duality. Exploring the duality allows the enfolded order in process to emerge and associates outcomes with the processes used in the design. Problems with process studies are discussed. Modes of study for process are distinguished from the standards that are often inappropriately exported from structure to process research."

Ohio State University.

Richter, Charles A., "An Assessment of Structured Analysis and Structured Design," *ACM SIGSOFT Software Engineering Notes*, Vol. 11, No. 4, August 1986, pp. 75-84.

ABSTRACT: "This paper is an assessment of the Structured Analysis and Structured Design methods of Tom DeMarco, Edward Yourdon, and Larry Constantine. The assessment is a reflection of the author's experience using Structured Analysis and Structured Design on a multi-person project during the later 1970s."

"Structured Analysis and Structured Design are of interest for three reasons. First, they are well-documented instances of *methods*. Second, they are in use today, thereby providing us with one view of the current state of practice. Finally, in their strengths and weaknesses, they may be representative of a class of current methods."

Software Technology Program, Microelectronics and Computer Technology Corporation (MCC).

Rouse, William B. and Kenneth R. Boff, "Workshop Themes and Issues: The Psychology of System Design," *System Design: Behavioral Perspectives on Designers, Tools, and Organizations* (ed. by William B. Rouse and Kenneth R. Boff), New York: North-Holland, 1987, pp. 7-17.

Discusses factors that should be considered in the development of advanced design support systems (nature of design, nature of designers, effects of organization, designer support systems, acceptance of support systems). Provides a good list of research questions.

Simon, Herbert A., "Decision Making and Problem Solving," *Interfaces*, Vol. 17, No. 5, September-October 1987, pp. 11-31.

ABSTRACT: The MS/OR community has, as its common mission, the development of tools and procedures to improve problem solving and decision making. This report discusses the advances needed to combine human thinking with intelligent machines to achieve a more productive society. Areas of high potential include research in expert systems, conflict resolution, agenda setting, decision making in an organizational setting, and empirical studies of individual behavior. The resources currently being applied to research in decision making and problem solving are modest and are not commensurate with the opportunities or the human resources available for exploiting them.

Stabell, Charles B., "Decision Support Systems: Alternative Perspectives and Schools," *Decision Support Systems,* Vol. 3, No.3, September 1987, pp. 243-231.

The design process as a decision structure.

Steward, Donald V., "The Design Structure System: A Method for Managing the Design of Complex Systems," *IEEE Transactions on Engineering Management*, Vol. EM-28, No. 3, August 1981, pp. 71-74.

ABSTRACT: "Systems design involves the determination of interdependent variables. Thus the precedence ordering for the tasks of determining these variables involves circuits. Circuits require planning decisions about how to iterate and where to use estimates. Conventional planning techniques, such as critical path, do not deal with these problems. Techniques are shown in this paper which can be used to develop an effective engineering plan, showing where estimates are to be used, how design iterations and reviews are handled, and how information flows during the design work. This information flow can be used to determine the consequences of a change in any variable on the rest of the variables in the system, and thus which engineers must be informed and which documents must be changed. From this, a critical path schedule can be developed for implementing the change. This method is ideally suited to an Automated Design Office where data, computer input and output, and communications are all handled through the use of computer terminals and data bases. However, these same techniques can also be effectively used in classical engineering environments."

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